UNIVERSITEIT GENT

FACULTY OF ENGINEERING AND ARCHITECTURE

Hydrodynamics of Vortex Reactors for Chemical Industry

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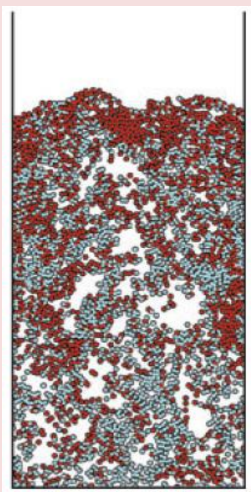
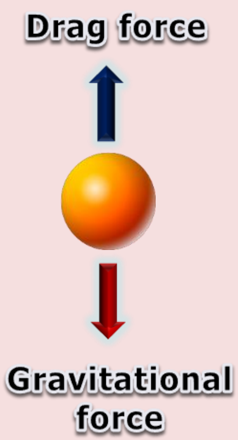
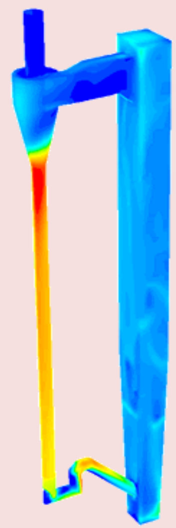
Introduction

Conventional Fluidized Bed [1]





Riser/Circulating Fluidized Bed [2]



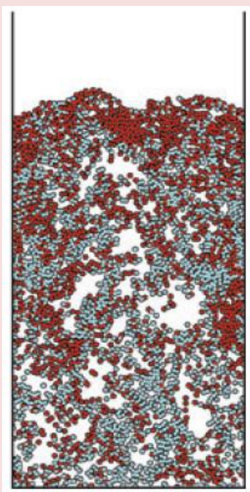
Limitations:
- Entrainment of particles at high gas flow rates
- Limited slip velocities (~ 1-2 m/s)

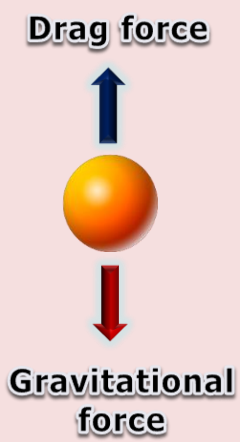
1. van Hoef et al., Ann. Rev. Fluid Mech. 40 (2008) 47-70
2. http://www.fluidcodes.co.uk/fbed.html

Introduction

Centrifugal instead of gravitational field → Process Intensification

Conventional Fluidized Bed [1]





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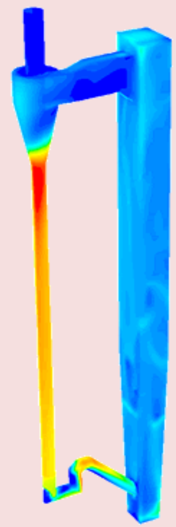

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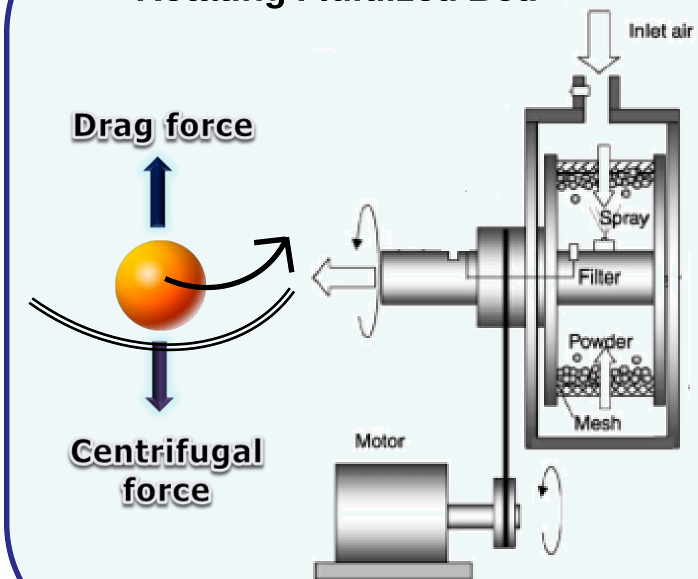
Rotating Fluidized Bed [3]



Advantages:
- Dense particle bed
- High gas feed flow rates
- Higher slip velocity
  → *higher heat and mass transfer*

1. van Hoef et al., Ann. Rev. Fluid Mech. 40 (2008) 47-70
2. http://www.fluidcodes.co.uk/fbed.html
3. adapted from Watano et al., Powder Tech.131 (2003) 250-255

Introduction

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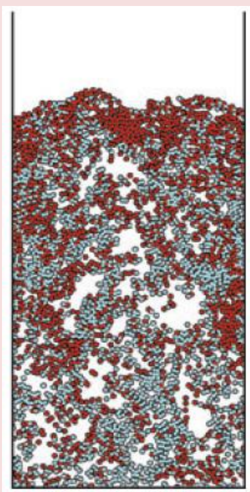

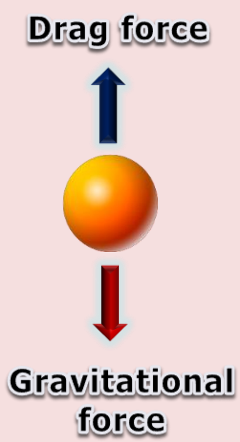

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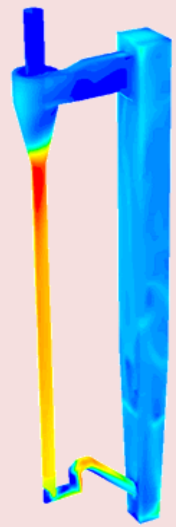

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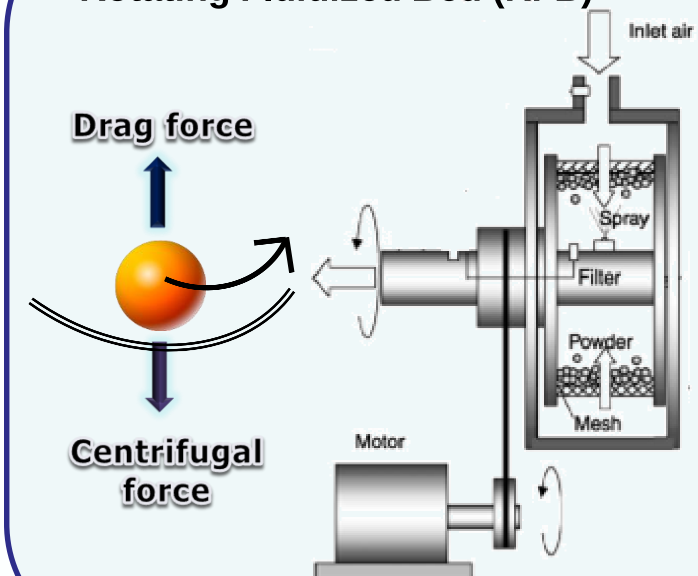
Rotating Fluidized Bed (RFB) [3]



Limitation:
- Mechanical moving parts cause abrasion

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2. http://www.fluidcodes.co.uk/fbed.html
3. adapted from Watano et al., Powder Tech.131 (2003) 250-255

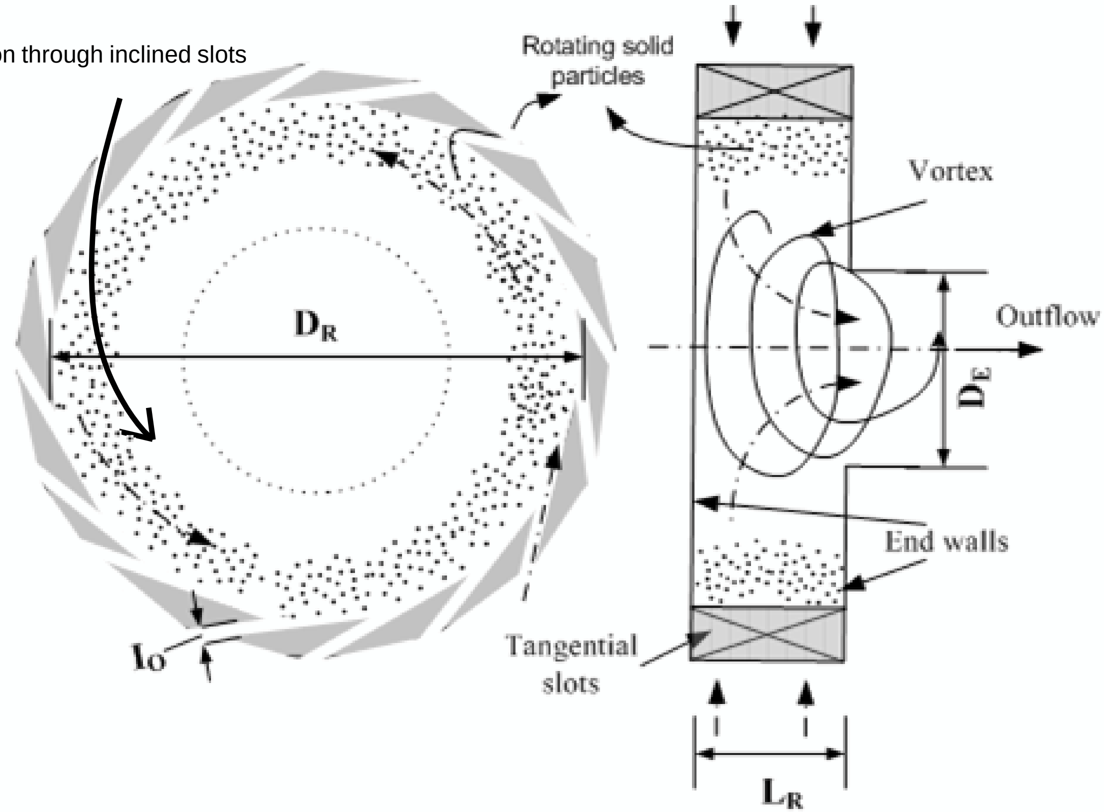
Introduction

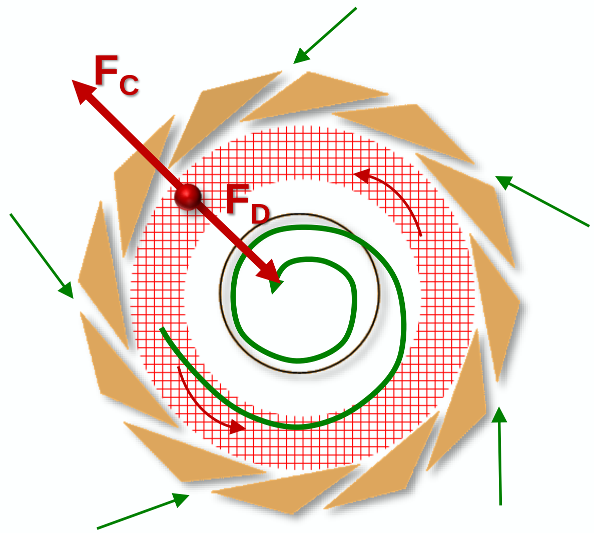
- **Overcome limitations of**
  - **Geometry**
  - **Throughput**
  - **Instability**
- **Process Intensification needed**
  - **More throughput in smaller reactor volume**
  - **Centrifugal field in a static geometry**

Introduction

Gas-Solid Vortex Reactor (GSVR)

Gas injection through inclined slots





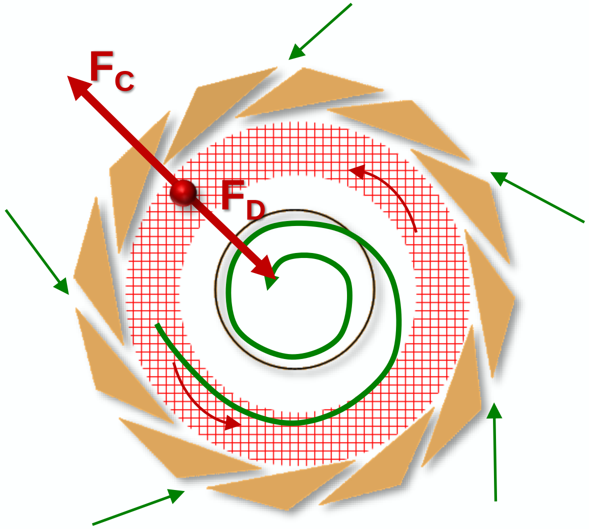
Fluidized Bed in Vortex Reactor

Introduction

Gas-Solid Vortex Reactor (GSVR)

- Advantages:
  - Higher slip velocity
  - Higher throughput operation
  - Enhanced heat and mass transfer

GFB



Fluidized Bed in Vortex Reactor

Introduction

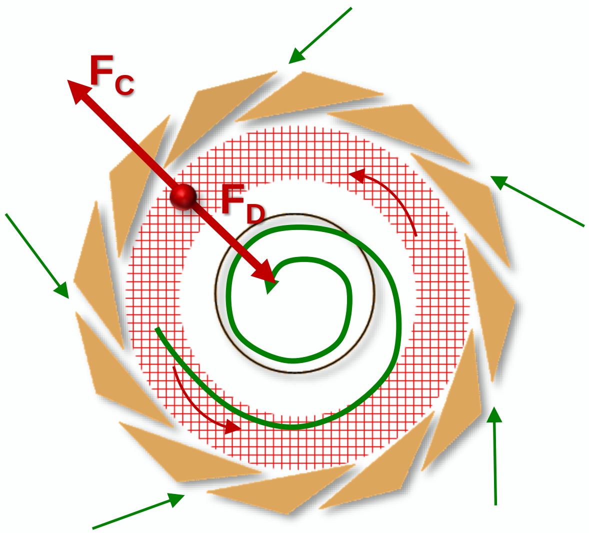
Gas-Solid Vortex Reactor (GSVR)

- Advantages:
  - Higher slip velocity
  - Higher throughput operation
  - Enhanced heat and mass transfer

  CFB

  - **No moving parts**

  RFB



Fluidized Bed in Vortex Reactor

Introduction

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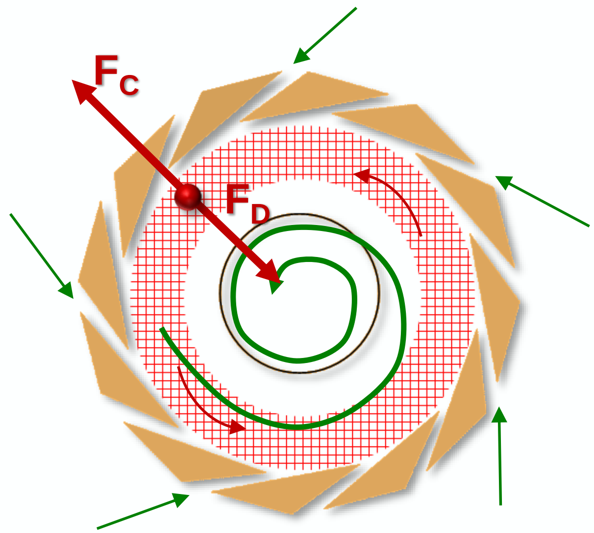

Fluidized Bed in Vortex Reactor

- Possible applications:
  - Pyrolysis of biomass
  - Drying
  - Fluidization of cohesive particles
  - Particle spray coating

Introduction

Gas-Solid Vortex Reactor (GSVR)

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  - **No moving parts**

  RFB

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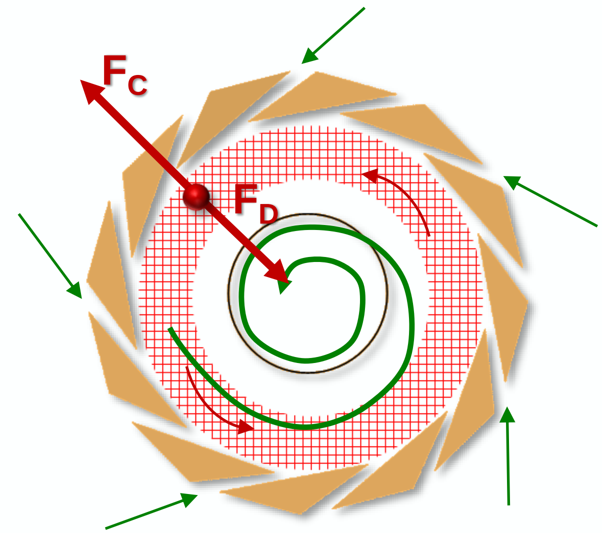


Fluidized Bed in Vortex Reactor

- **Claims investigated:**
  - **Dense bed flow operation**
  - **High slip velocities**

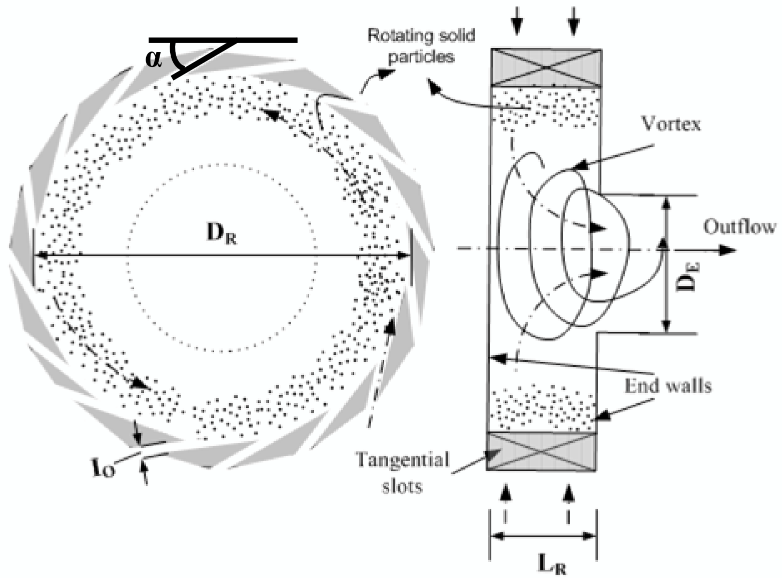
Outline

- Introduction
- **Numerical methodology**
- Results and discussion
  - *Effect of gas flow rate*
  - *Effect of particle density*
  - *Effect of particle diameter*
- Conclusions

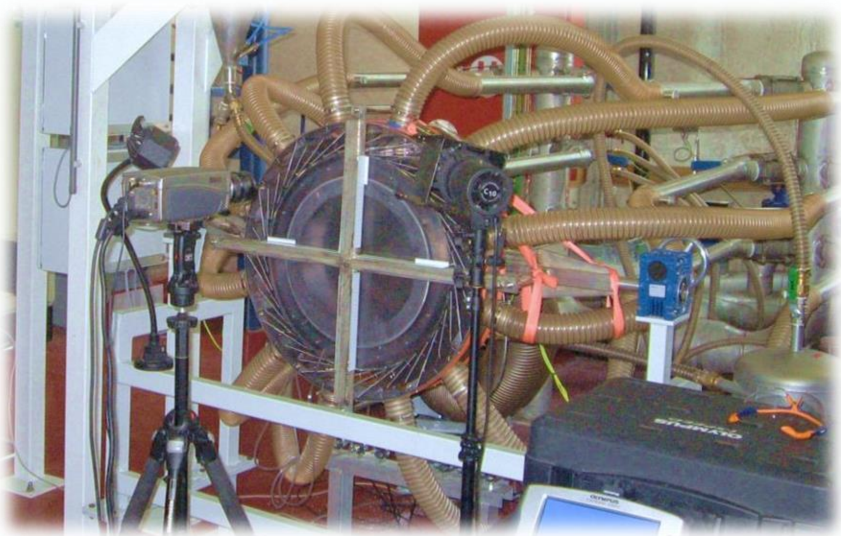
Numerical methodology

GSVR geometrical parameters

D_R	**0.54 m**
D_E	0.15 m
L_R	0.1 m
Injection slots	36
l_o	0.002 m
α	10°



Experimental GSVR setup in Laboratory for Chemical Technology



Numerical methodology

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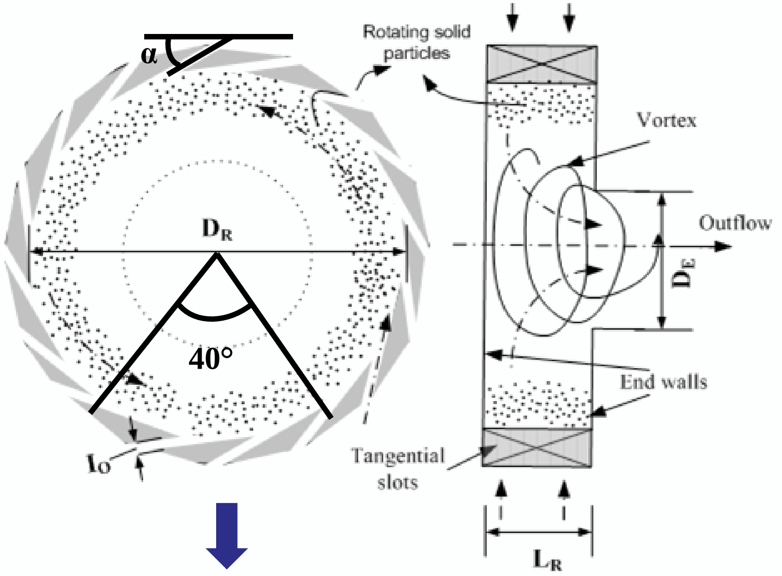
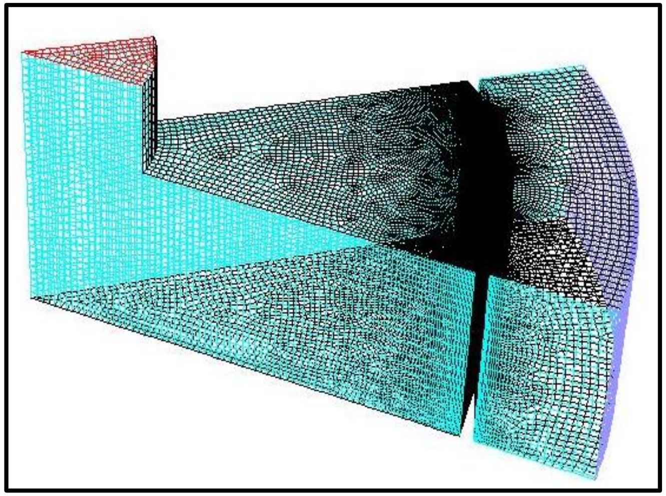


GSVR simulation parameters

Mesh geometry: 3-D, 40° section of GSVU cold flow unit



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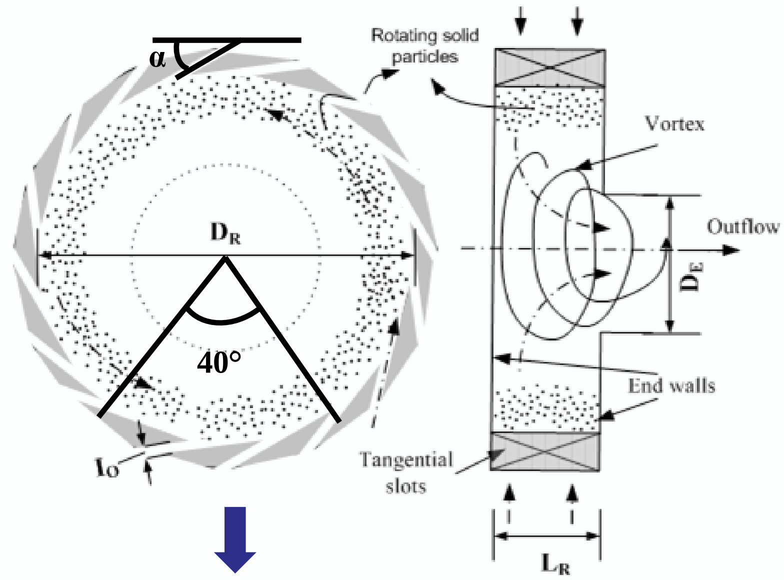
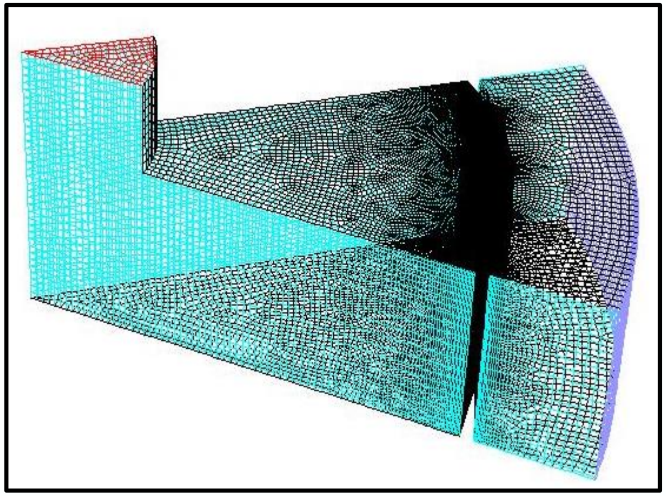


GSVR simulation parameters

Mesh geometry: 3-D, 40° section of GSVU cold flow unit

Eulerian Eulerian simulation, KTGF used for solid phase

RNG k-ε turbulence model used (per phase)



Numerical methodology

GSVR geometrical parameters

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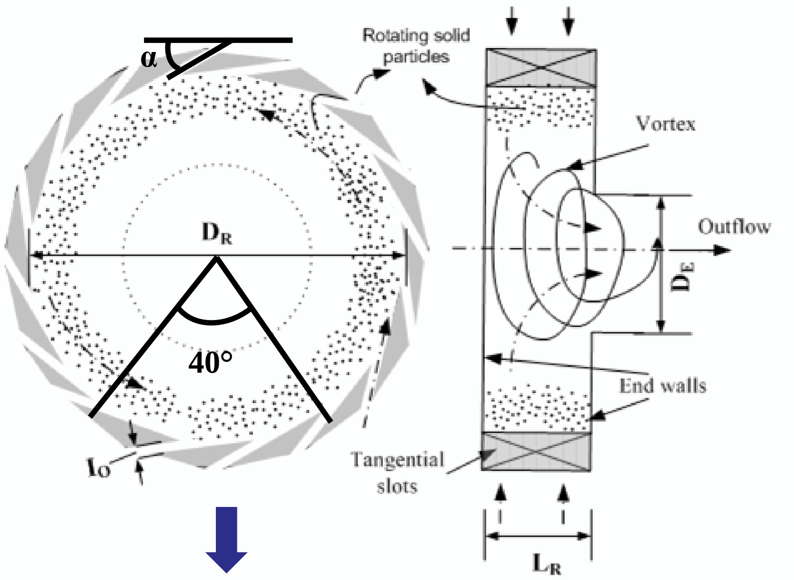
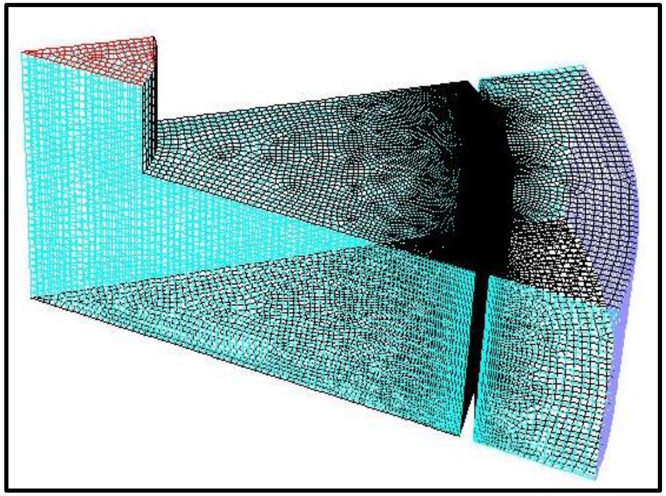
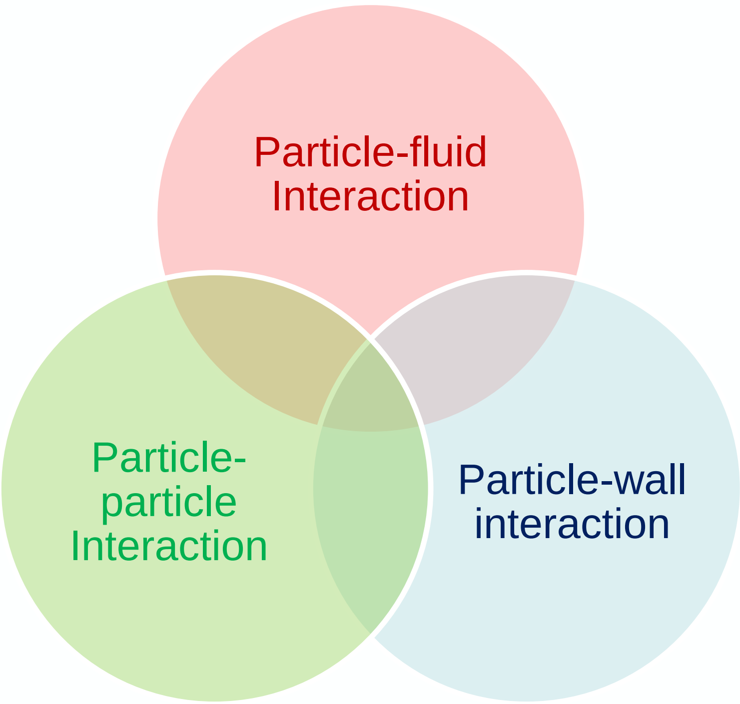




GSVR simulation parameters

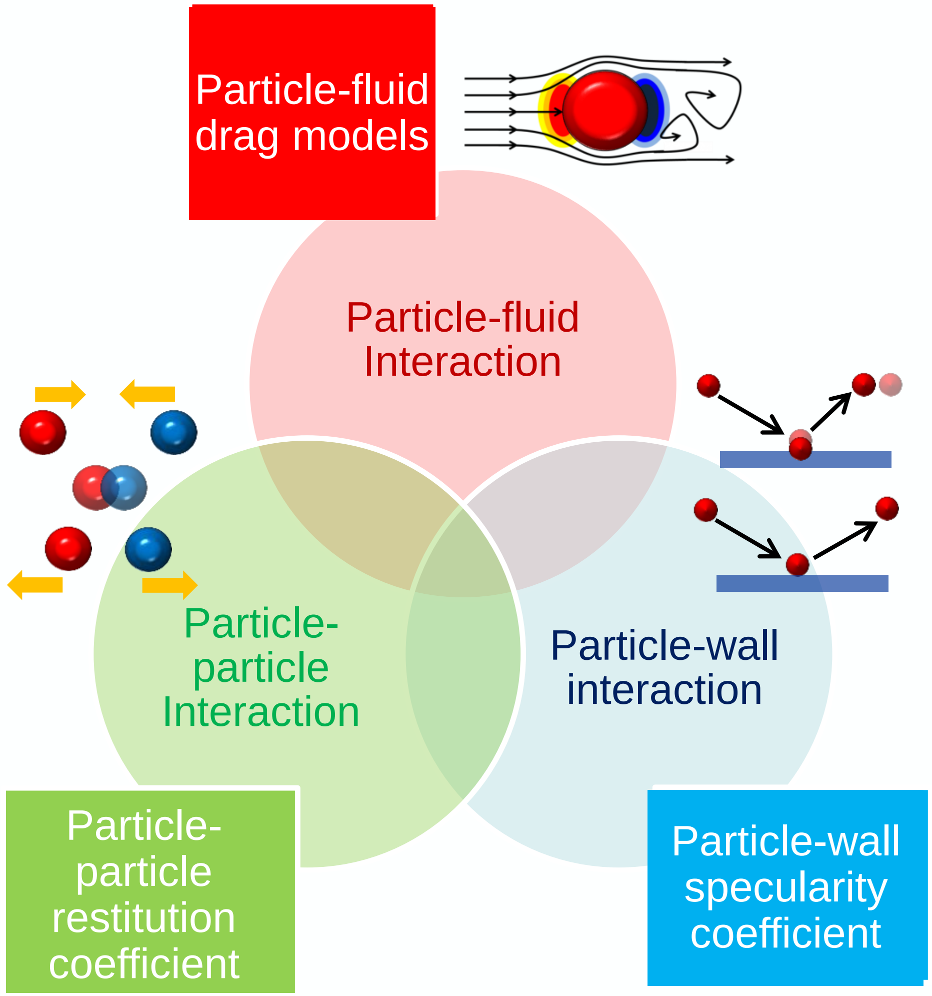
- Mesh geometry: 3-D, 40° section of GSVU cold flow unit
- Eulerian Eulerian simulation, KTGF used for solid phase
- RNG k-ε turbulence model used (per phase)
- Transient cold flow simulations, semi-batch operation
- Gas used: Air (Incompressible, 1.225 kg/m³)

Validation with Experimental data



Three main numerical parameters affecting GSVR flow

Validation with Experimental data



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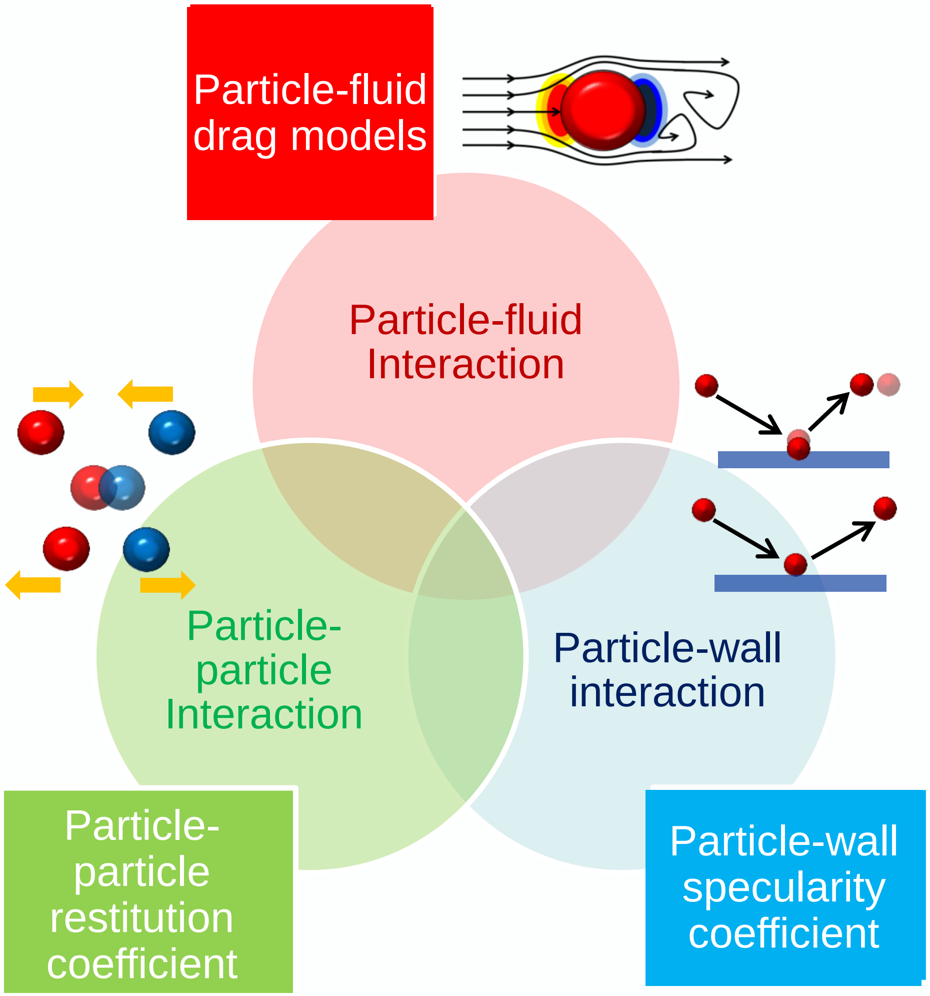
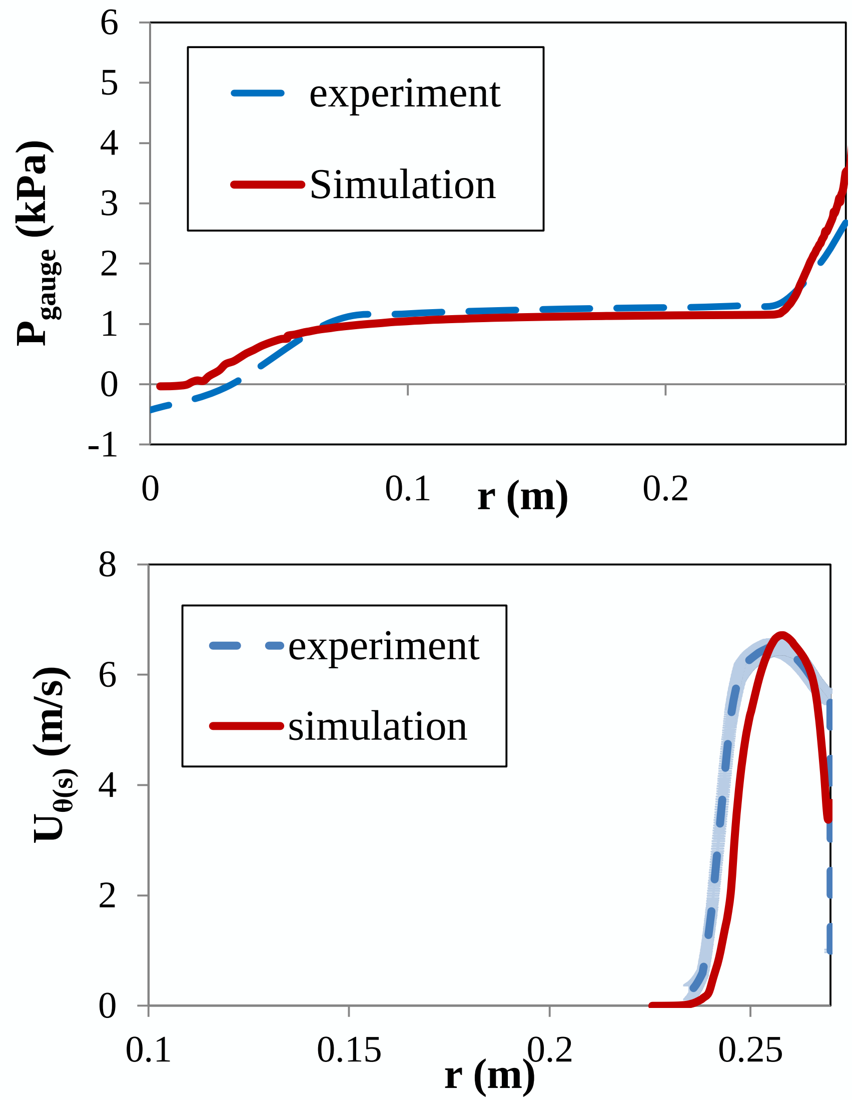


Three main numerical parameters affecting GSVR flow

High Density Polyethylene(HDPE), 1 mm, 2 kg



Gas flow rate: 0.5 Nm^3/s

Outline

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- **Results and discussion**
  - *Effect of gas flow rate*
  - *Effect of particle density*
  - *Effect of particle diameter*
- Conclusions

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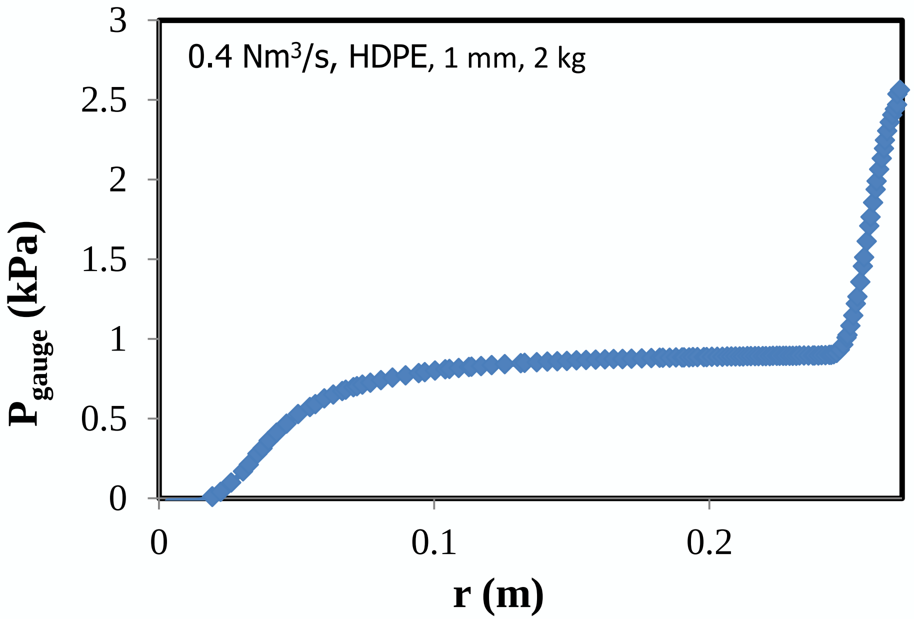
Material: HDPE (950 kg/m^3)
Particle diameter: 1 mm
Bed mass: 2 Kg

Gas flow rate (Nm^3/s)	Gas Injection velocity at slots (m/s)
0.15	15
0.3	30
0.4	42
0.5	55
0.65	70
0.8	85

Key flow features investigated:
- Bed pressure drop
- Solids azimuthal velocity
- Bed solids volume fraction
- Slip velocities between the phases

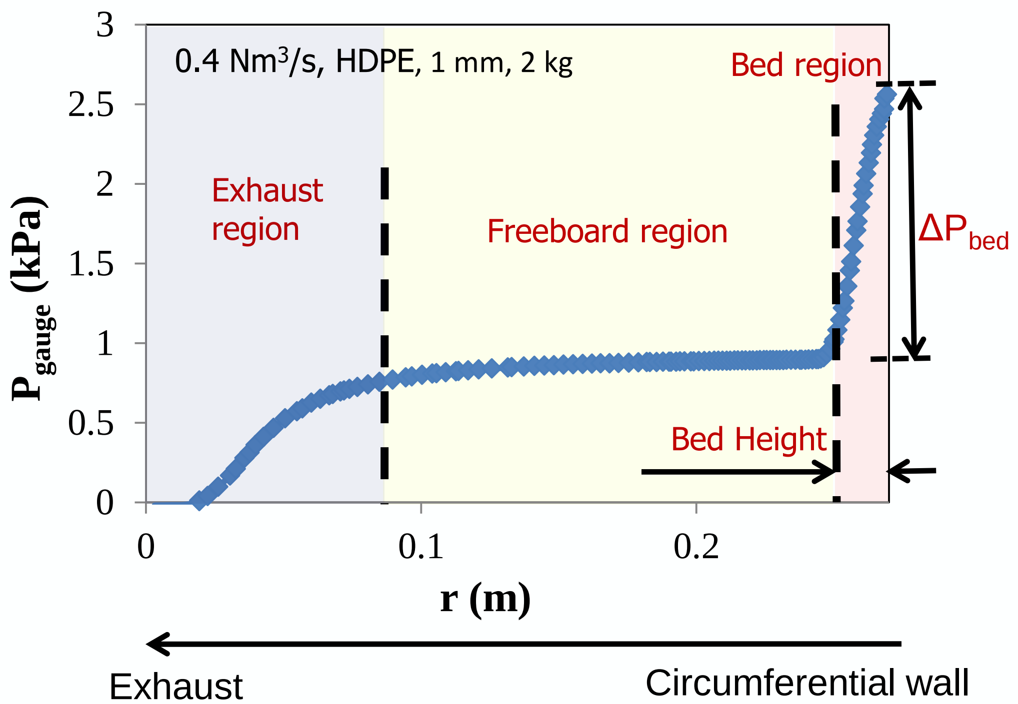
GSVR radial pressure profile



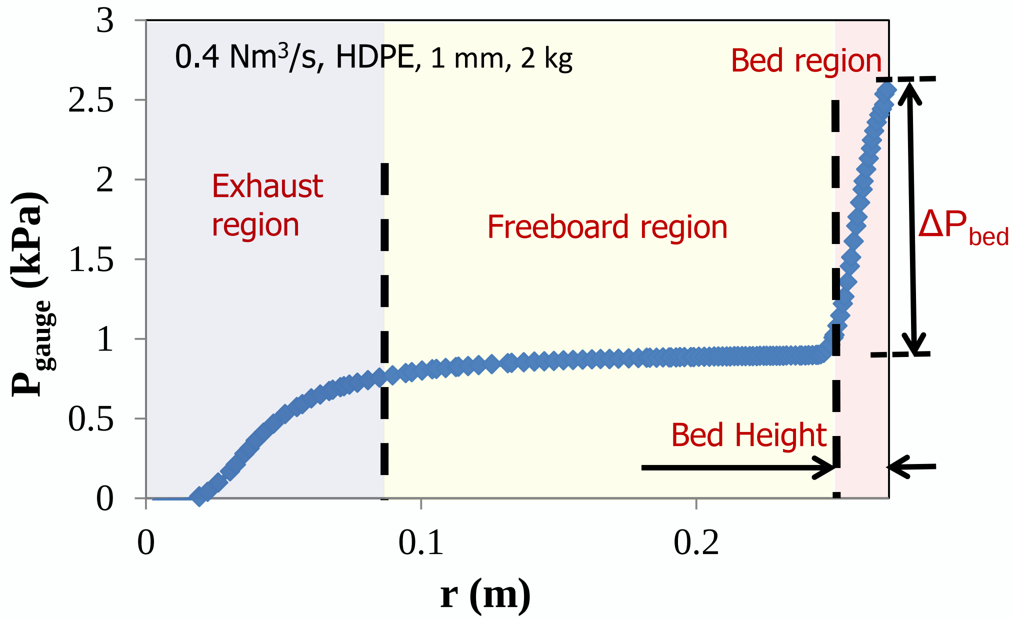
Exhaust

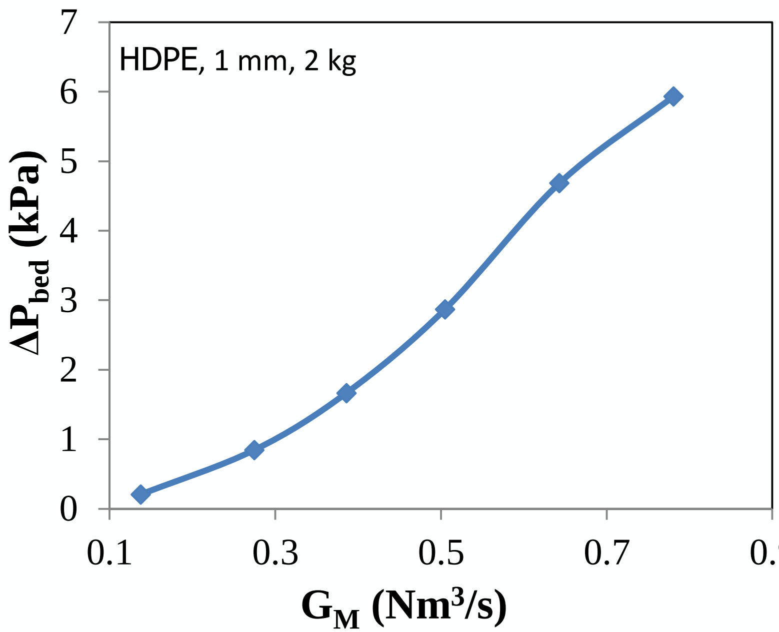
Circumferential wall

GSVR radial pressure profile

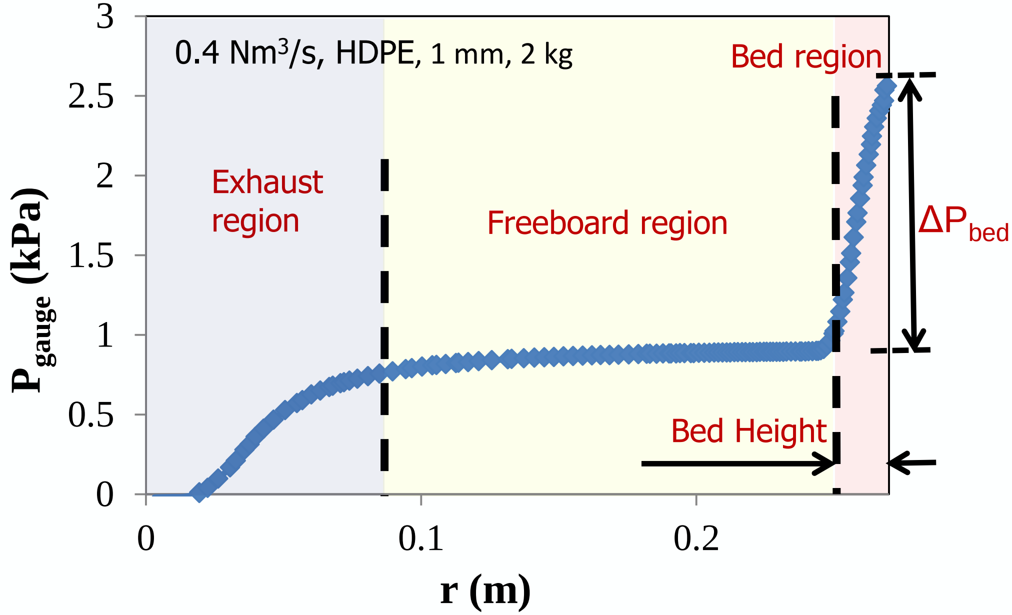


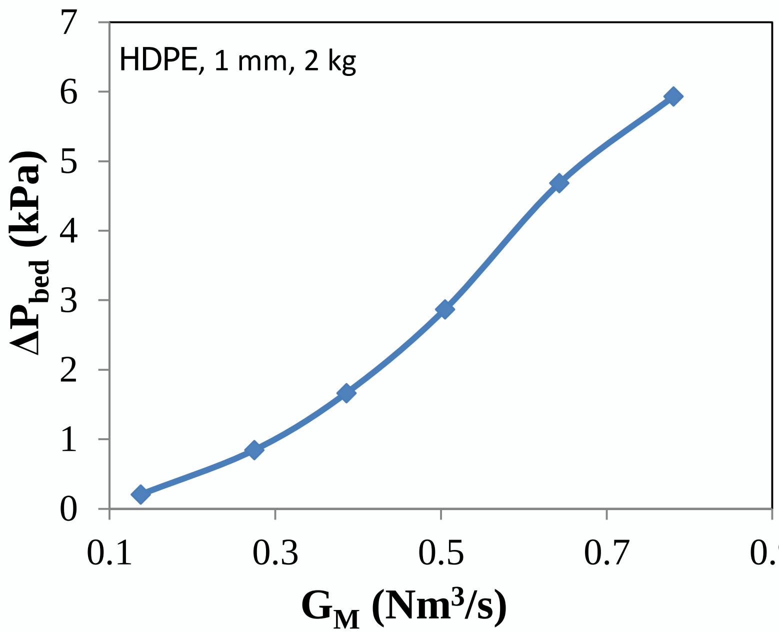
Bed pressure drop

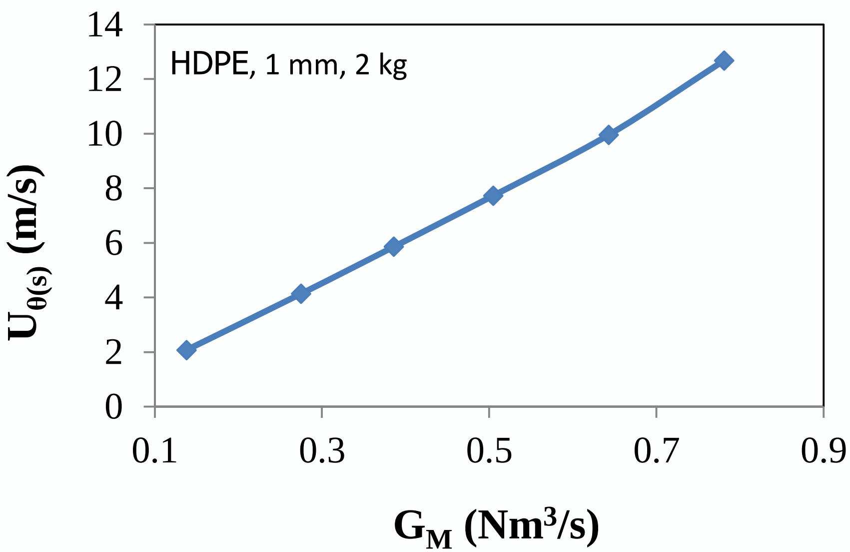




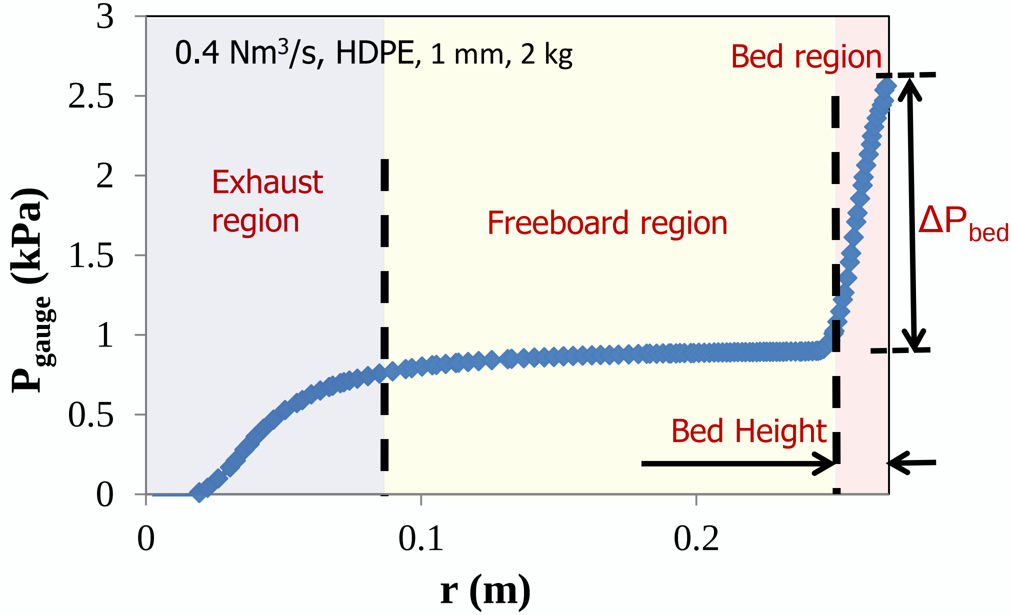
Solids velocity

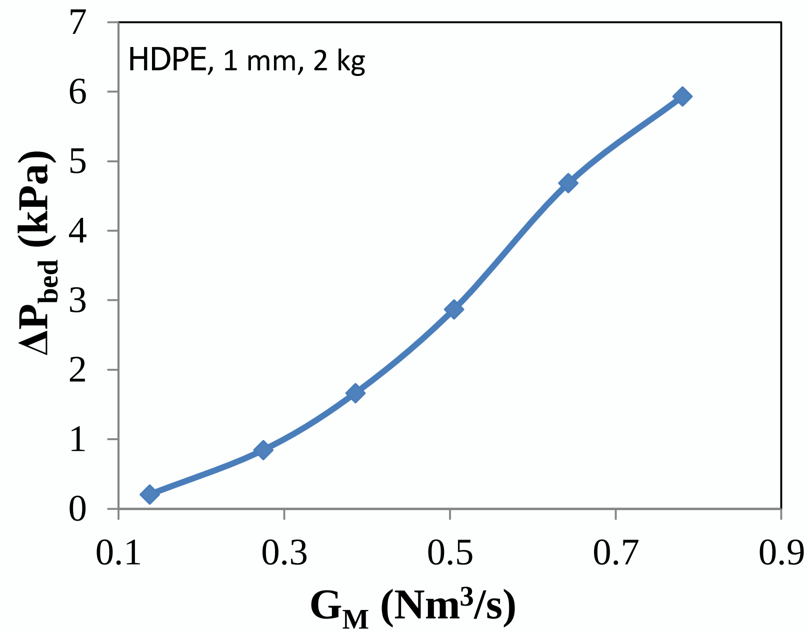


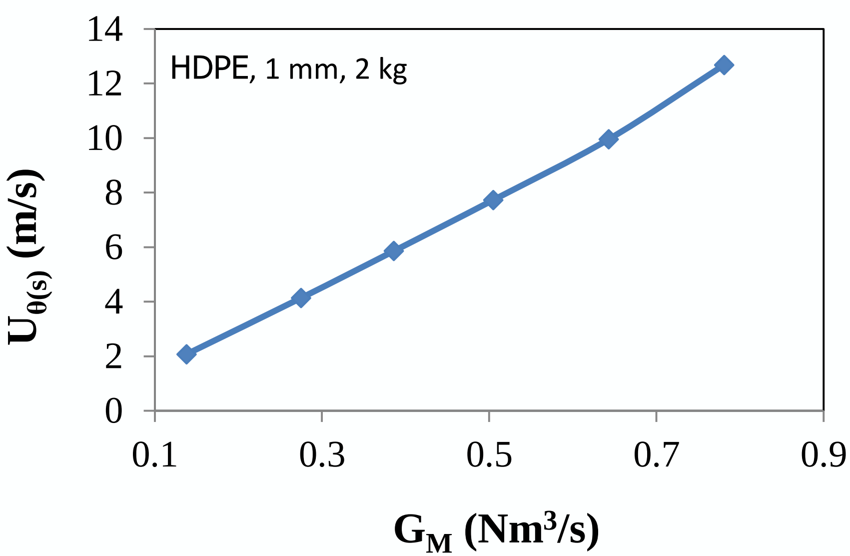


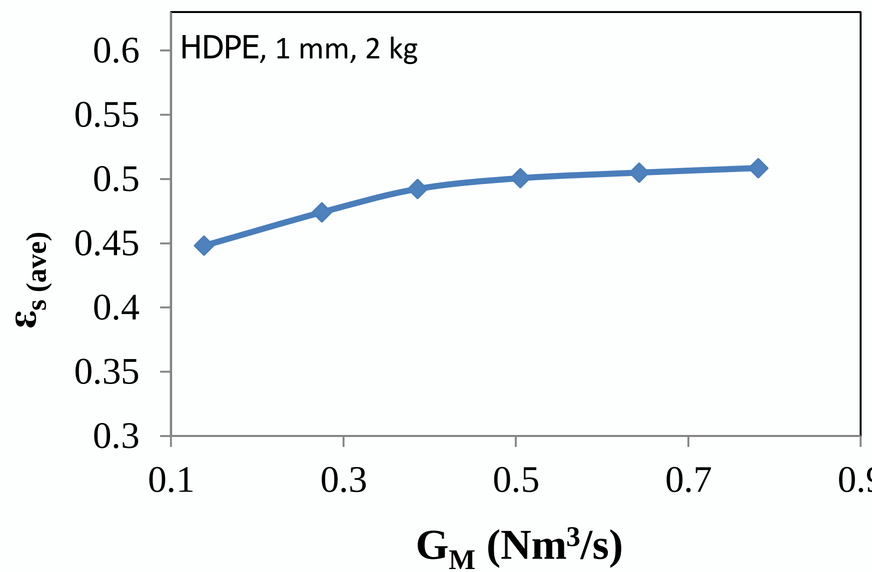


Solids volume fraction









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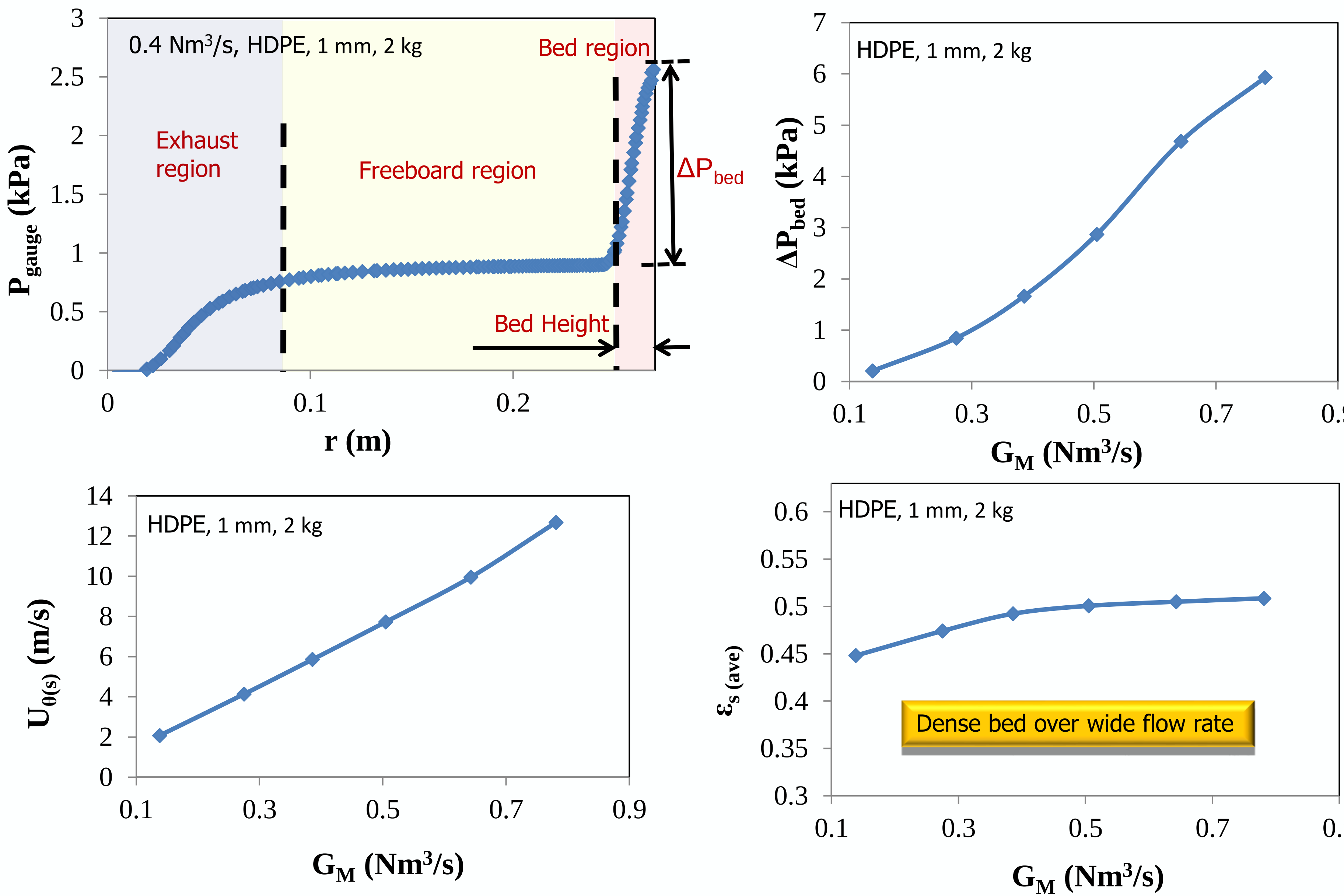
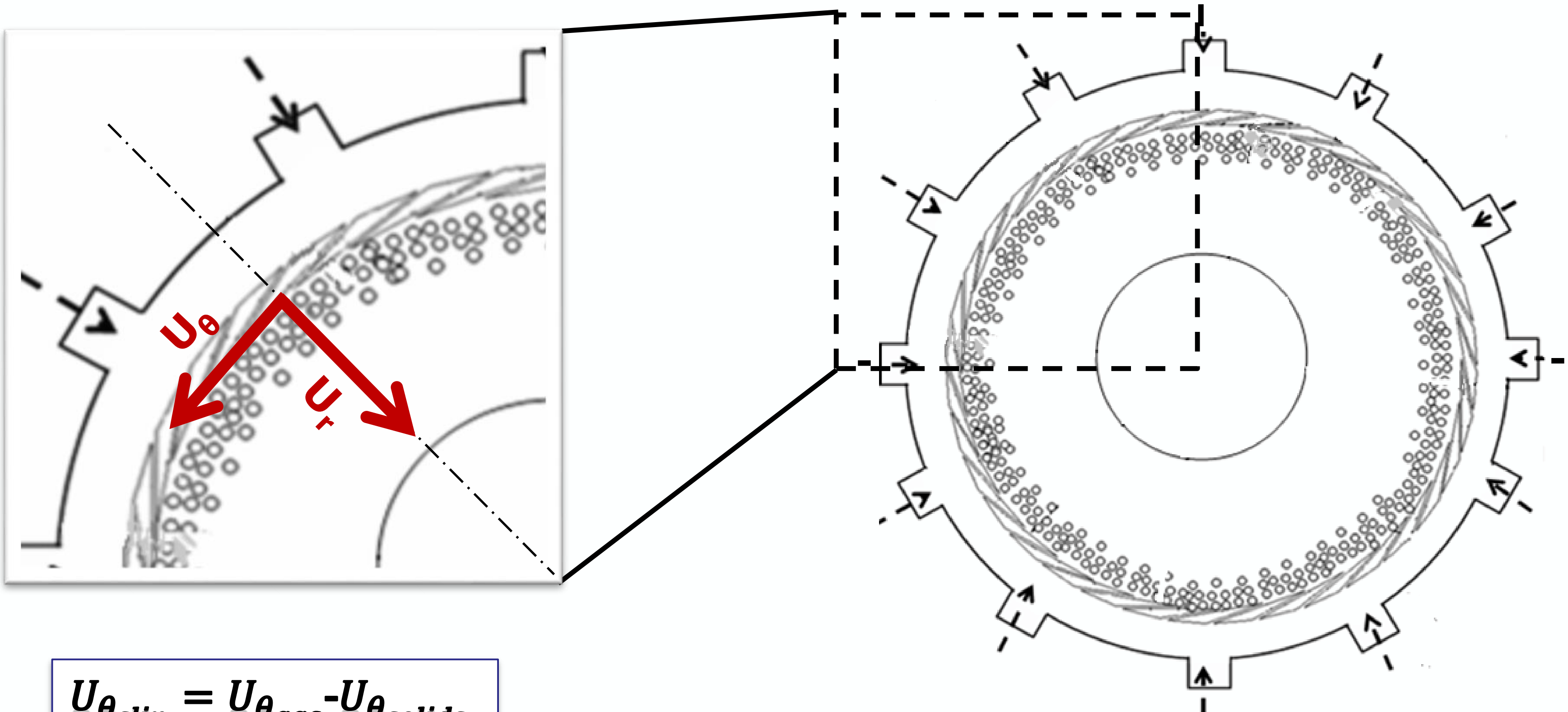


Slip velocity

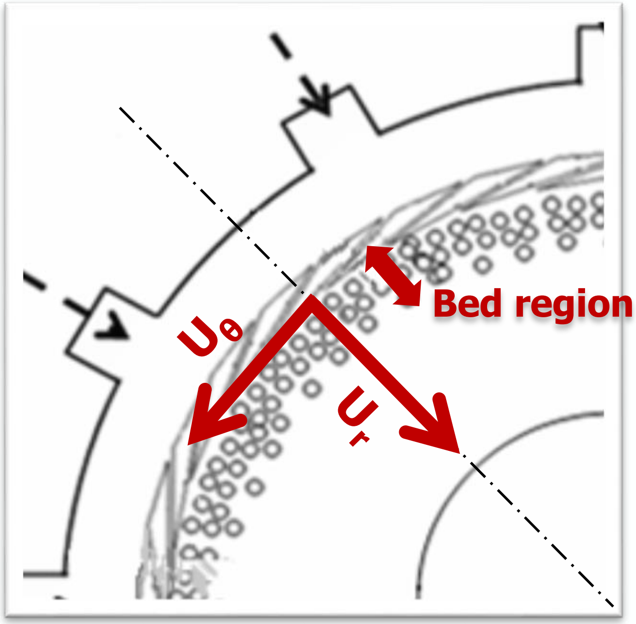


$$U_{\theta_{slip}} = U_{\theta_{gas}} - U_{\theta_{solids}}$$

$$U_{r_{slip}} = U_{r_{gas}} - U_{r_{solids}}$$

$$U_{slip} = \sqrt{U^2_{\theta_{slip}} + U^2_{r\,slip}}$$

Slip velocity



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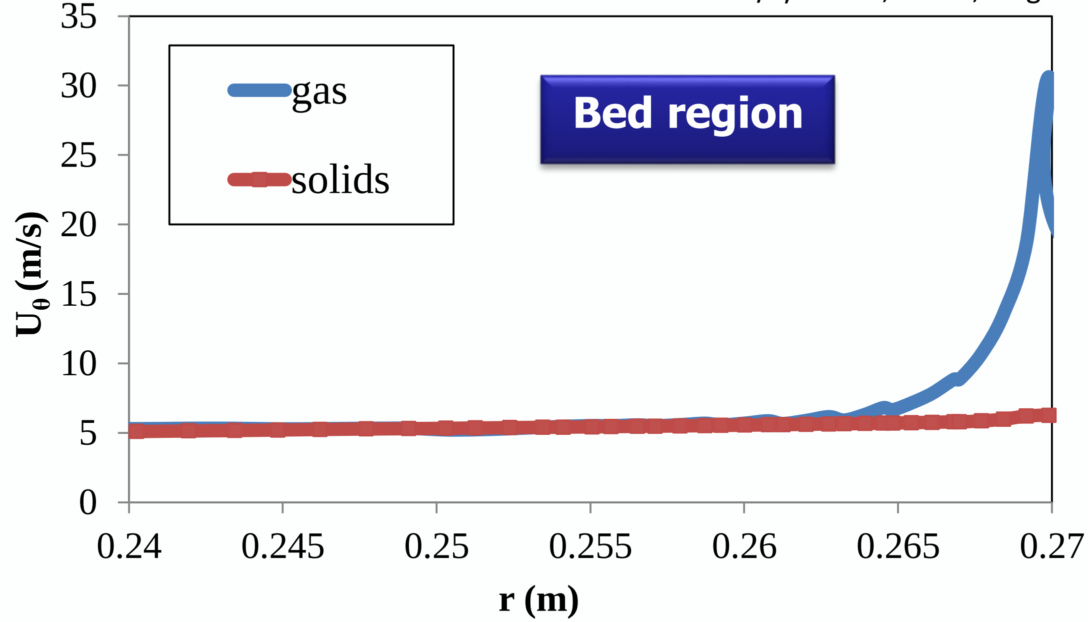
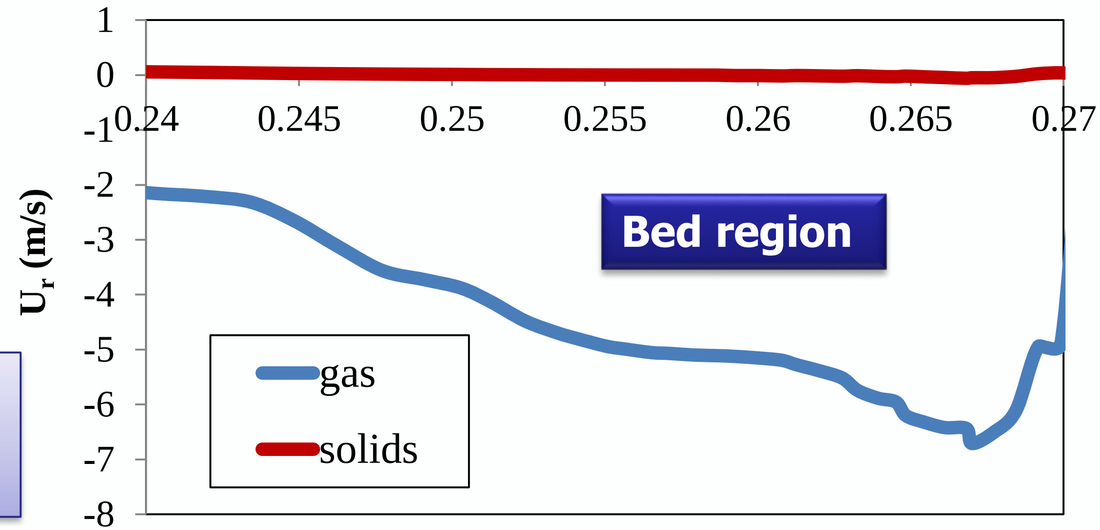
0.4 Nm^3/s, HDPE, 1 mm, 2 kg





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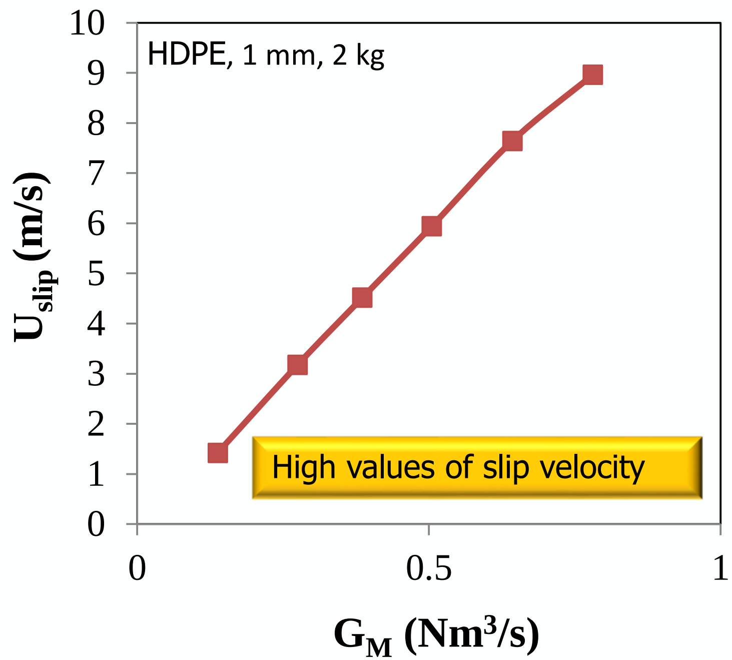

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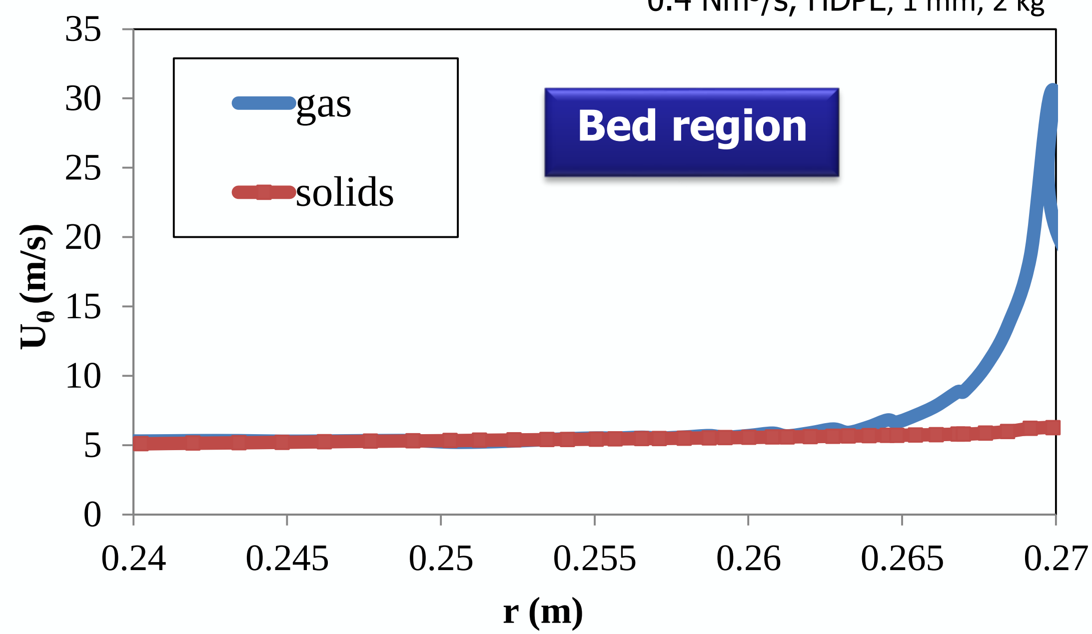

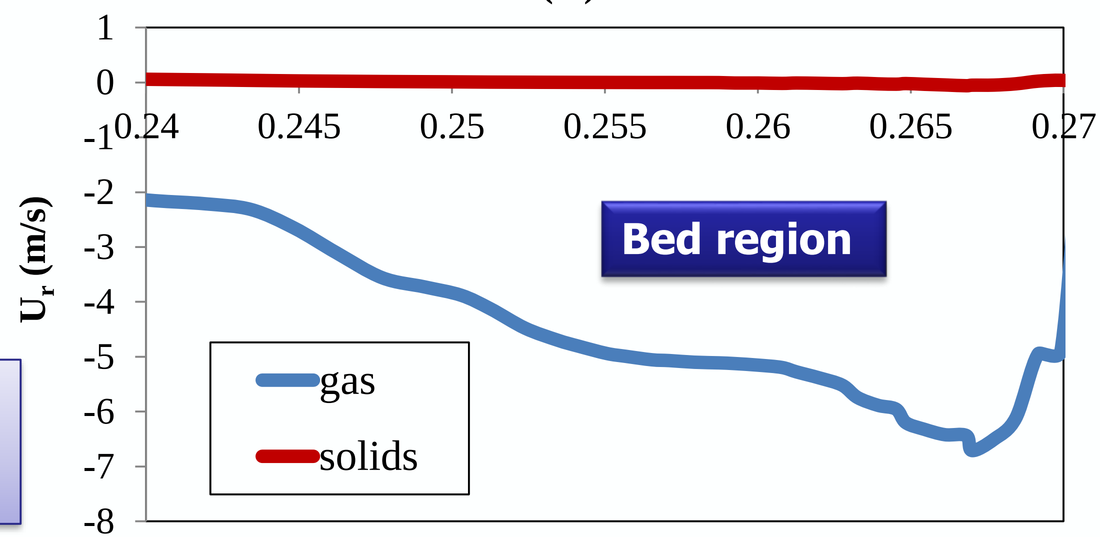

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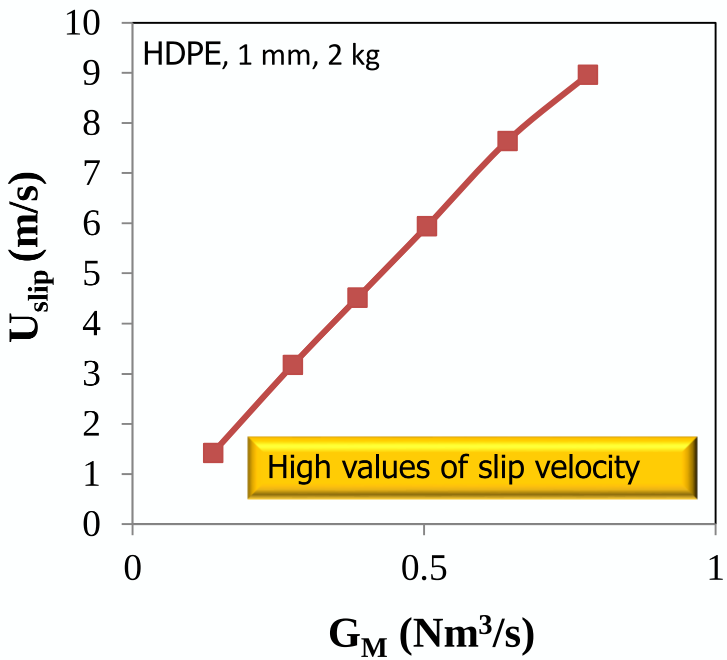
Slip velocity



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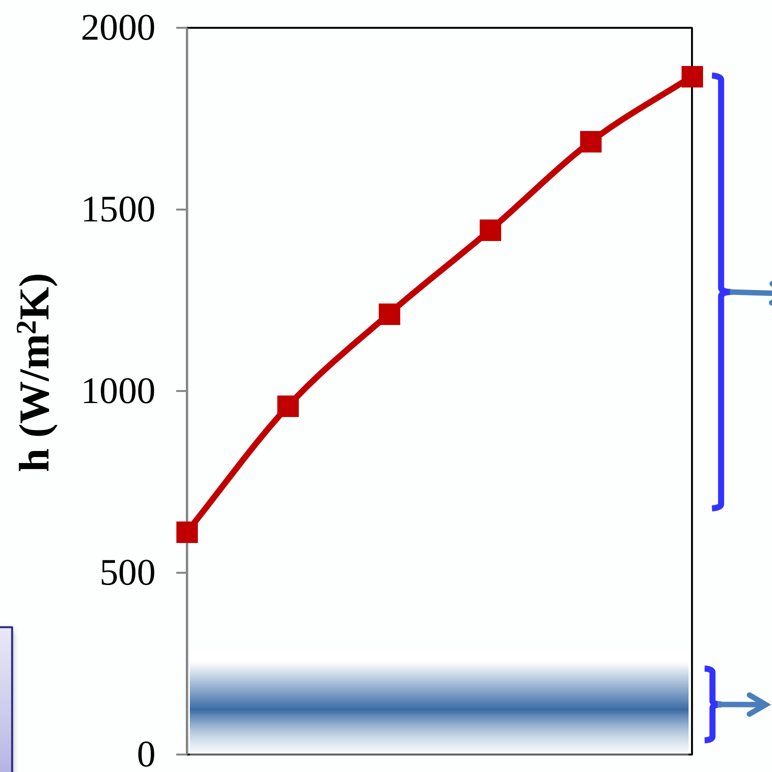
$$U_{r_{slip}} = U_{r_{gas}} - U_{r_{solids}}$$

$$U_{slip} = \sqrt{U^2_{\theta_{slip}} + U^2_{r\,slip}}$$

Now, Gunn correlation[4] can be used to calculate Nu and the heat transfer coefficient (h)

$$Re = f(U_{slip})$$

$$Nu = f(\varepsilon_{s(ave)}, Pr, Re)$$

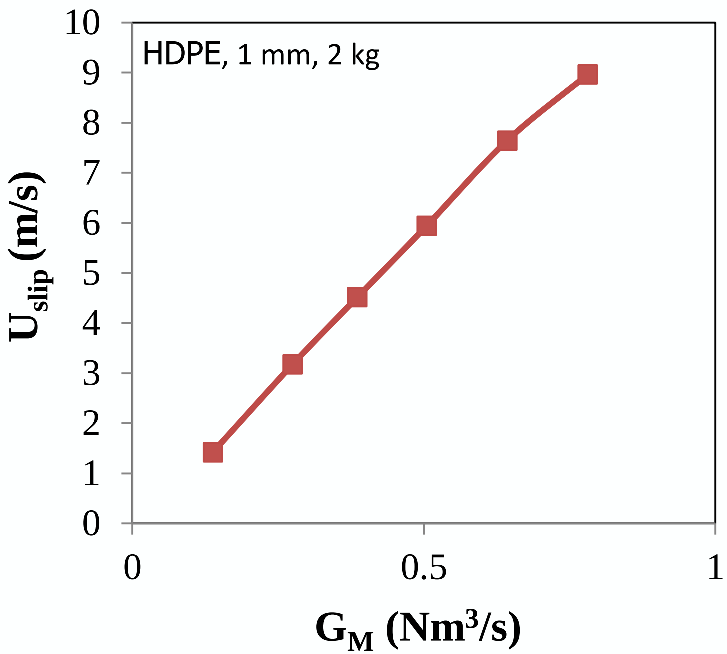


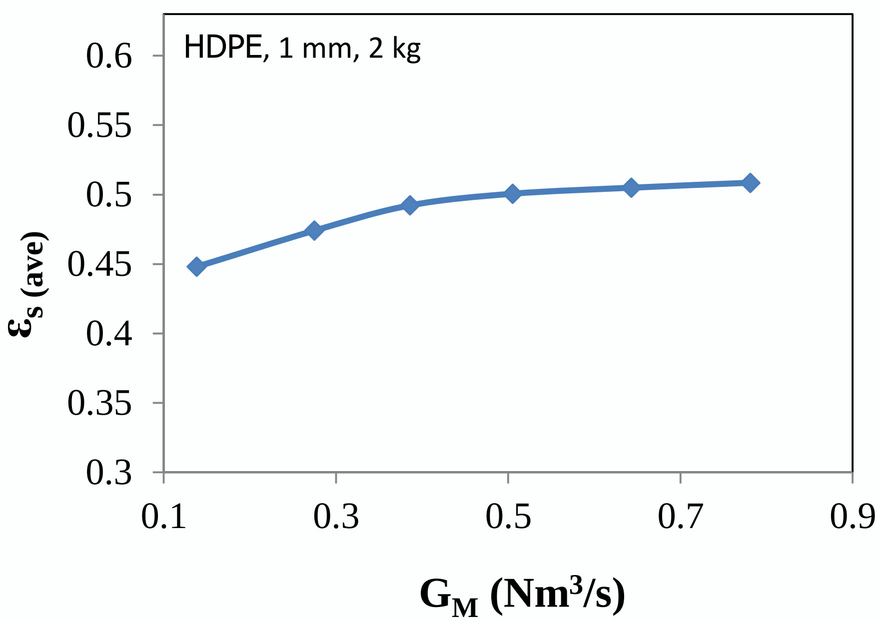
Range for GSVR: ~600 – 1900 W/(m^2 K)

Typical range for static fluidized beds and risers: ~100 – 200 W/(m^2 K)

1. Gunn, Int. J. Heat Transfer Sci. 21 (1978) 467

Summary





- High gas-solid slip velocities can be achieved
- Dense particle bed over wide range of flow rate suggests stable operation
- Dense beds leads to higher solids capacity per reactor volume

~ leads to Process Intensification

Outline

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  - *Effect of particle diameter*
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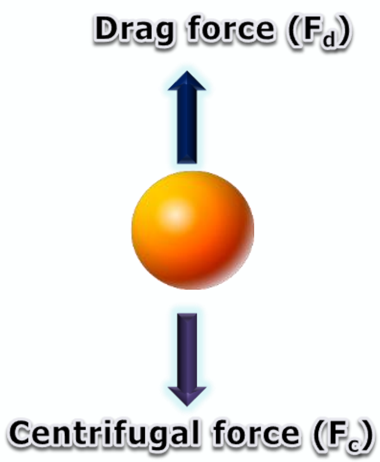
Gas flow rate: 0.4 Nm^3/s
Particle diameter: 1 mm
Bed mass: 2 kg

Density (kg/m^3)	Representative material
1900	Sand
950	HDPE
450	Biomass

Key flow features investigated:

- Bed pressure drop
- Solids azimuthal velocity
- Bed solids volume fraction
- Slip velocities between the phases

Effect on drag force



Drag force $\propto$ Total cross section of solids

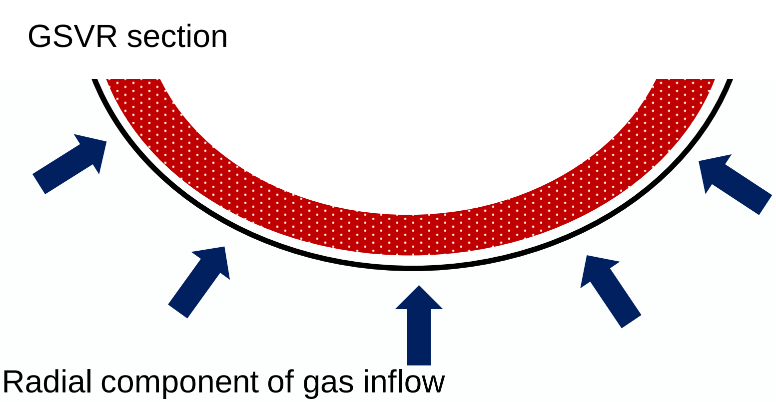
$$\text{Total cross section available in solids } (A_T) = \left(\frac{A_P}{V_P}\right) \times V_T$$

Where, $\left(\frac{A_P}{V_P}\right)$ – specific cross sectional area of particle

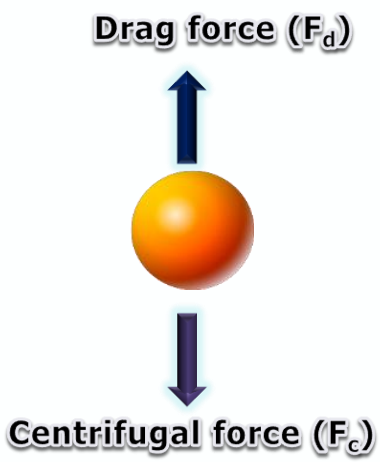
V_T - total volume of solids in the system

As, particle diameter for different materials constant,

$$\left(\frac{A_P}{V_P}\right) = \text{constant}$$



Effect on drag force



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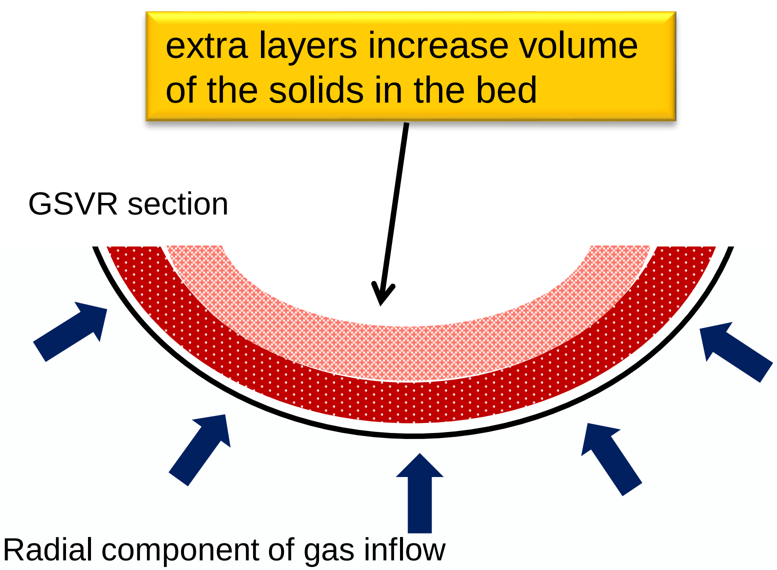
However, as particle density decreases and mass of solids is kept constant,

$V_T \uparrow$ $A_T \uparrow$

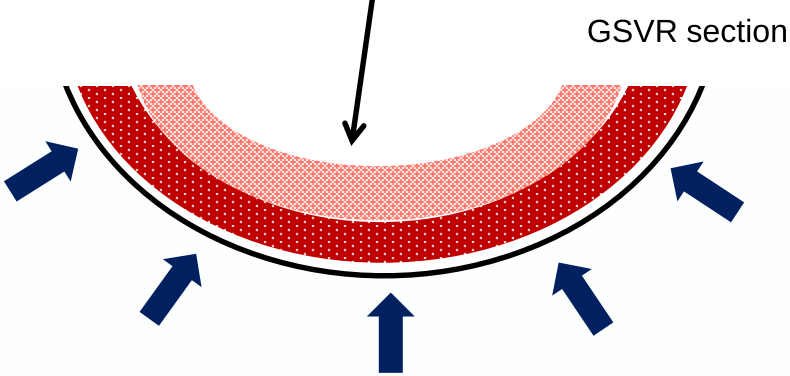


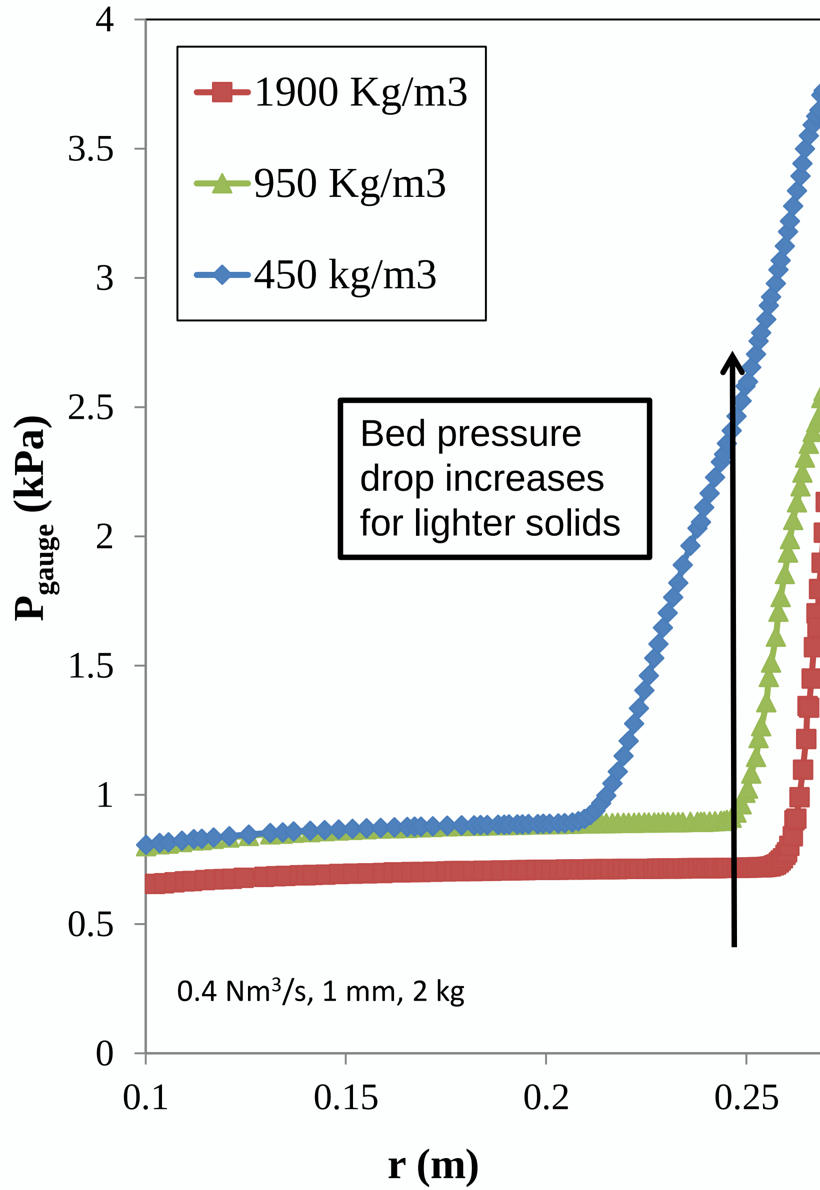
Drag force on bed increases due to higher solids cross sectional area

GSVR pressure profile

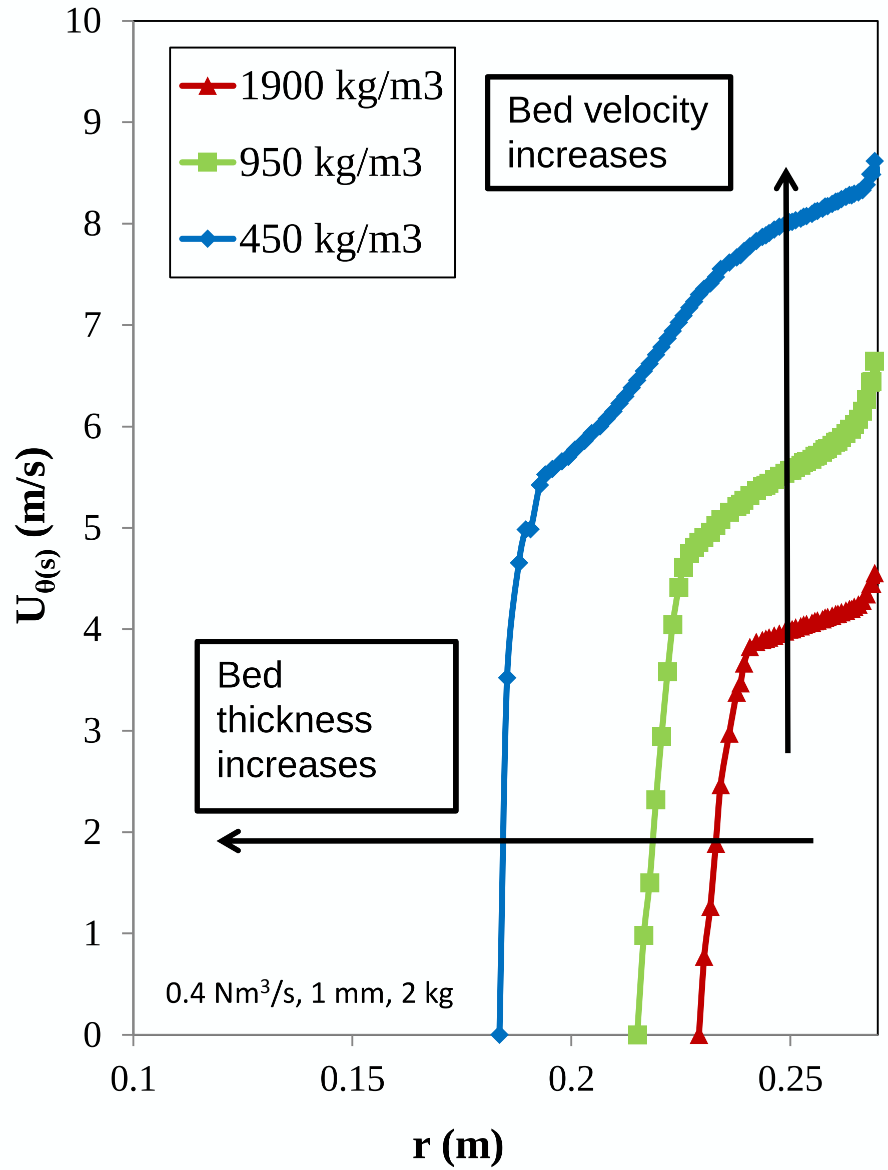
Higher drag force → Higher bed pressure drop

extra layers increase volume of the solids in the bed





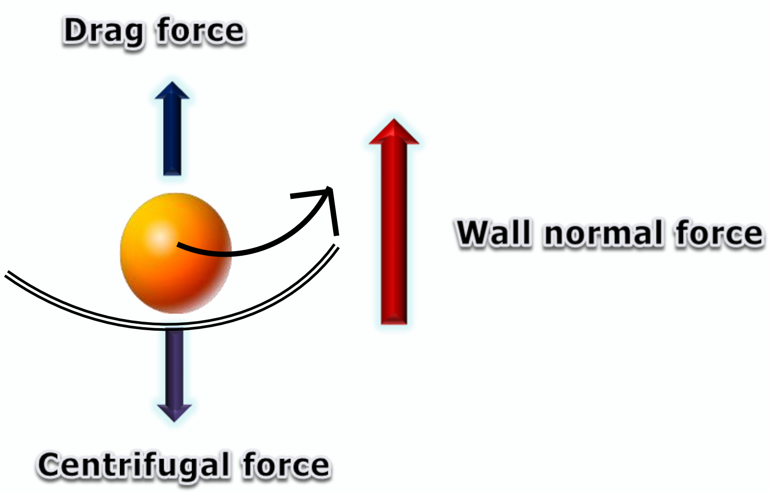
Solids velocity

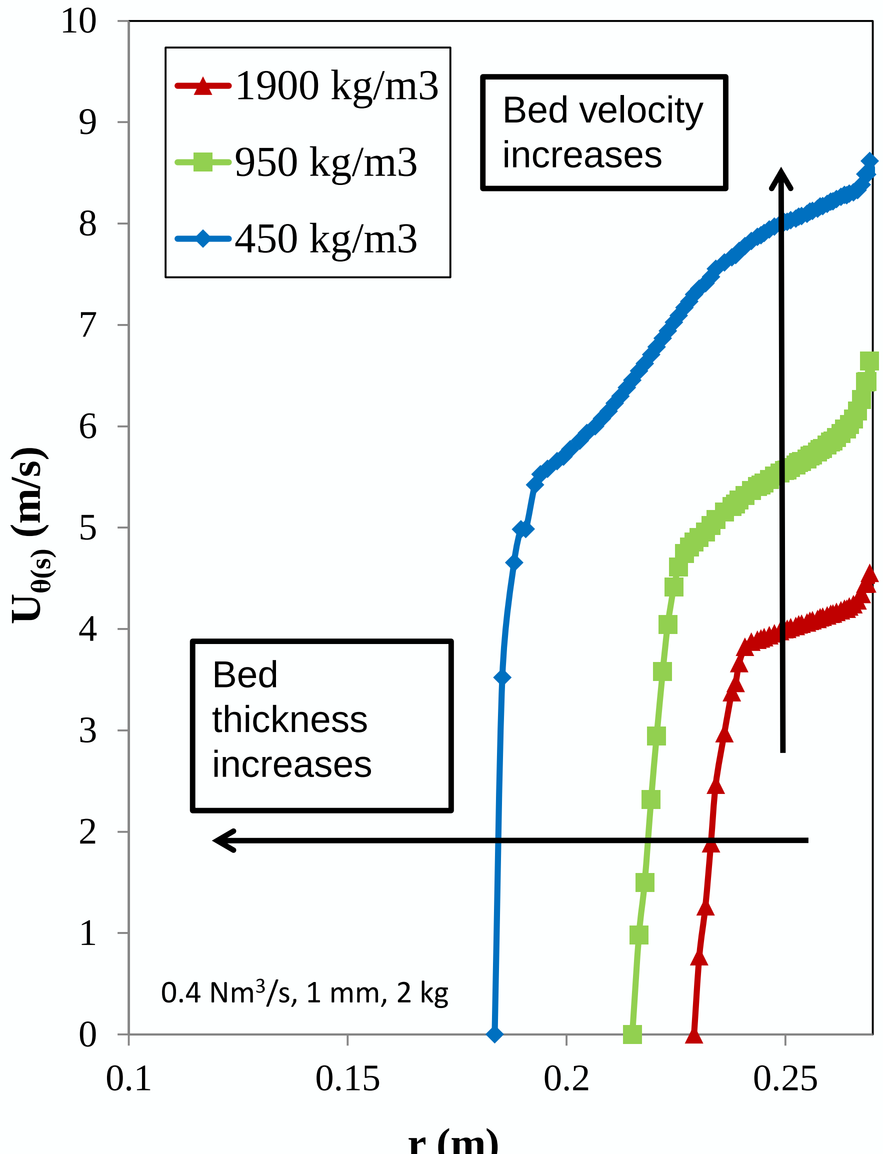


Solids velocity

In the radial direction:

Wall normal force
= centrifugal force – drag force





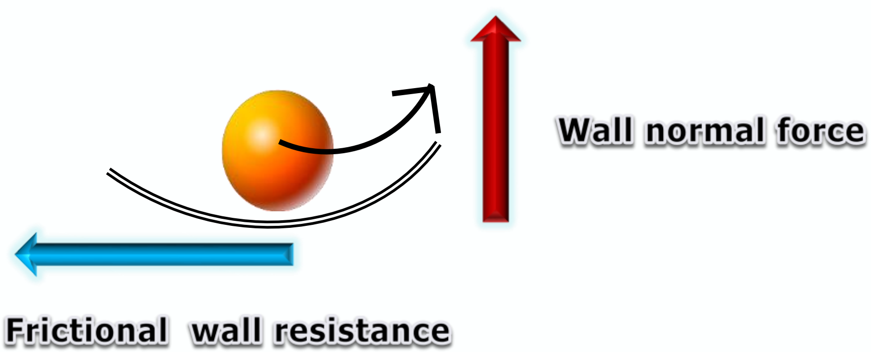
Solids velocity

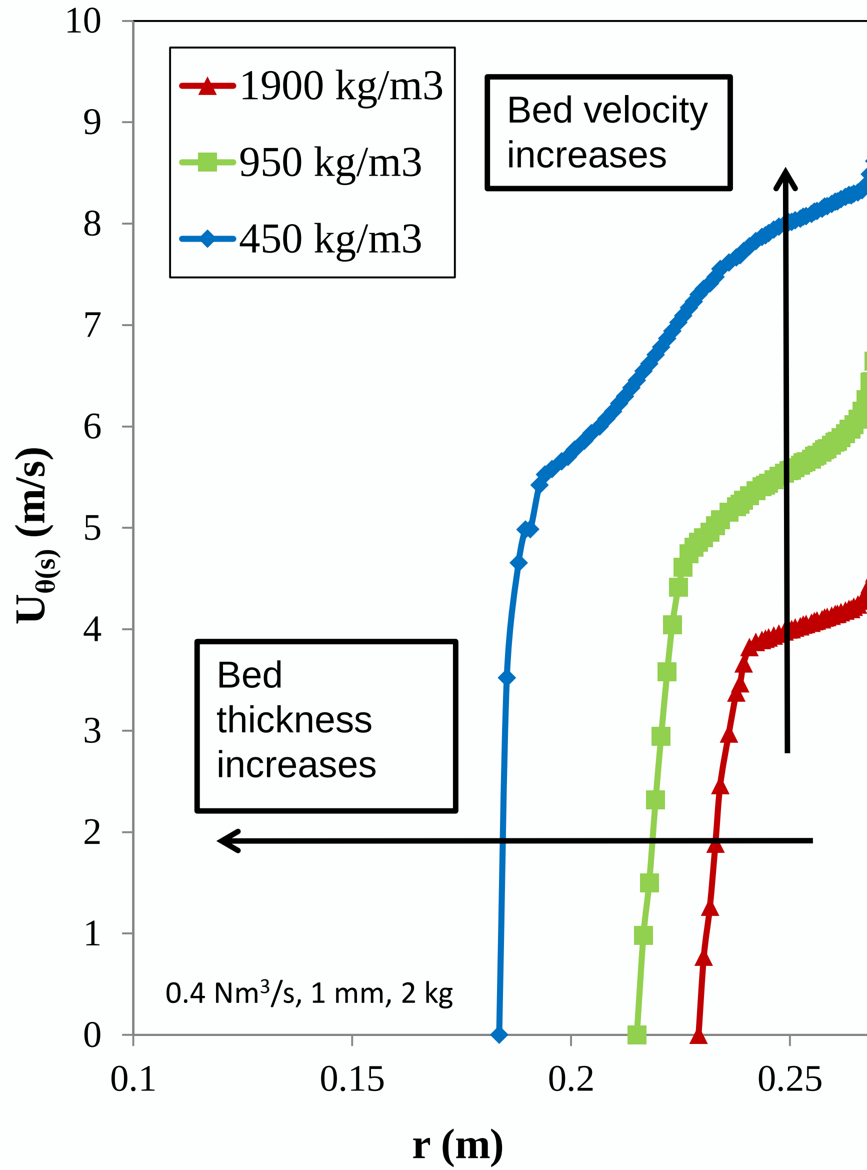
In the radial direction:

Wall normal force
= centrifugal force – drag force

In the azimuthal direction:

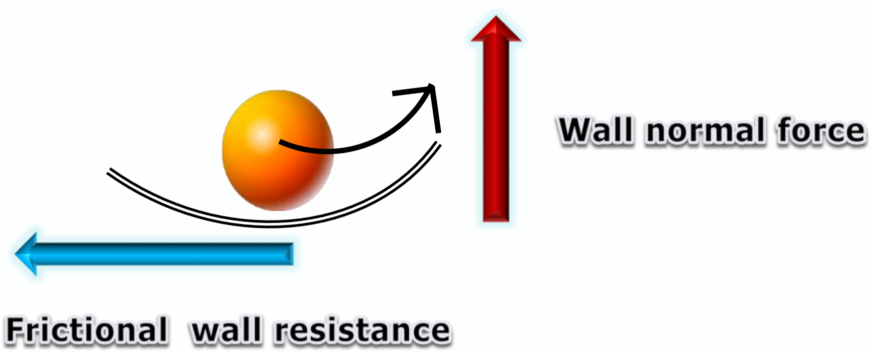
Frictional wall resistance
= μ(wall normal force)

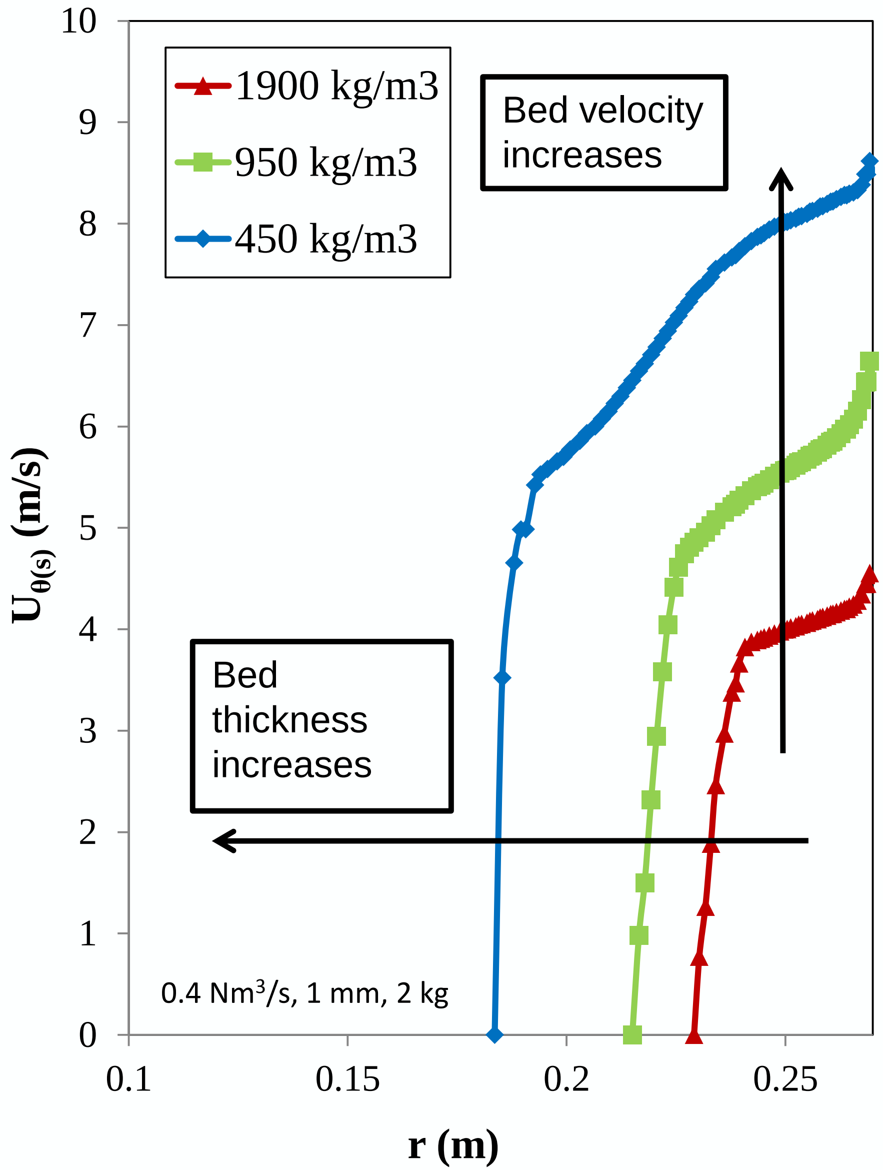




Solids velocity

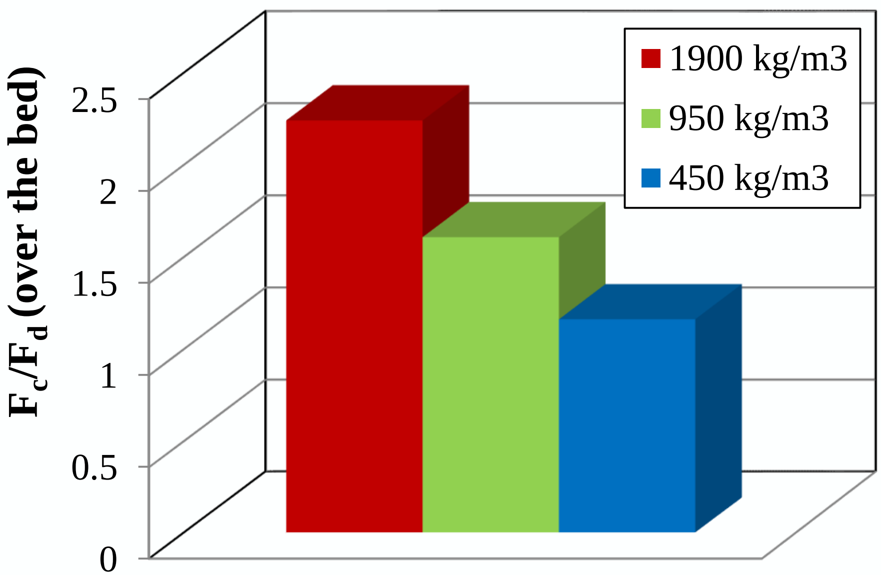
Higher drag force → Reduced wall friction



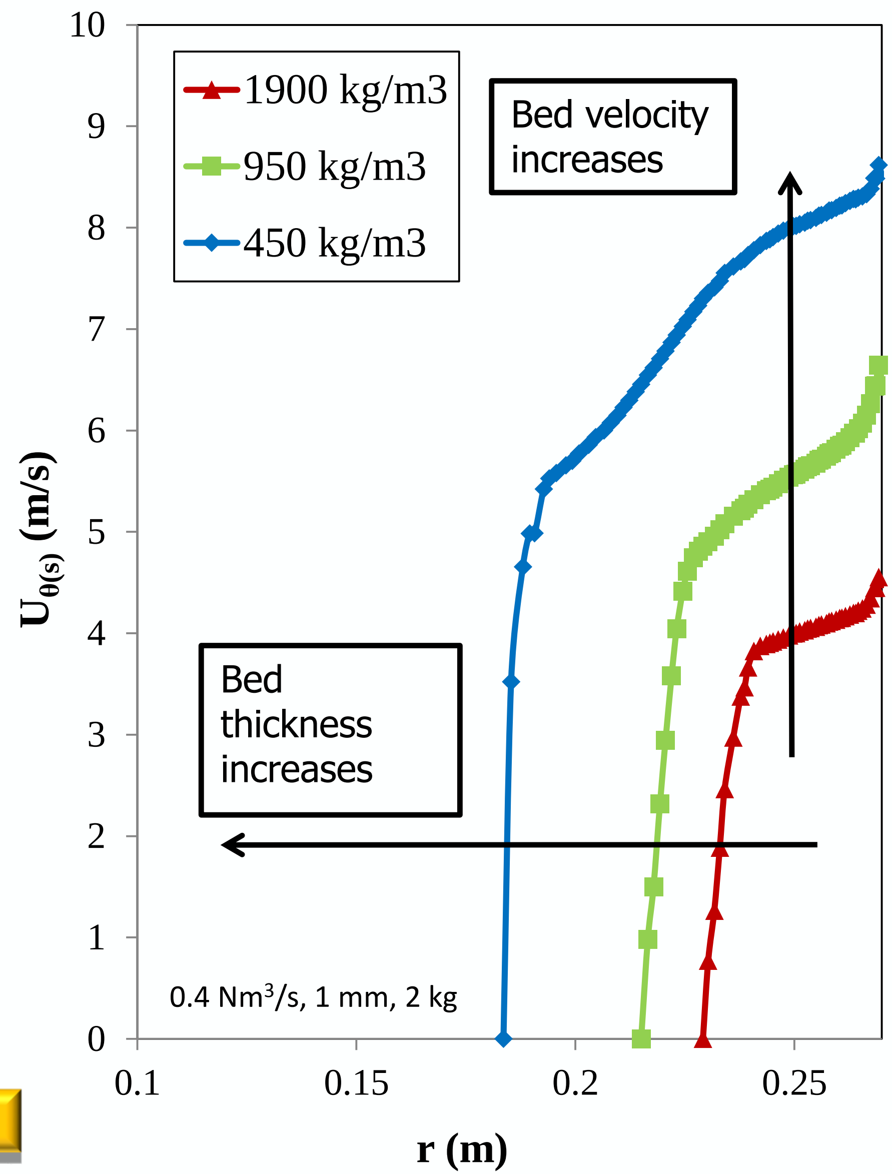


Solids velocity

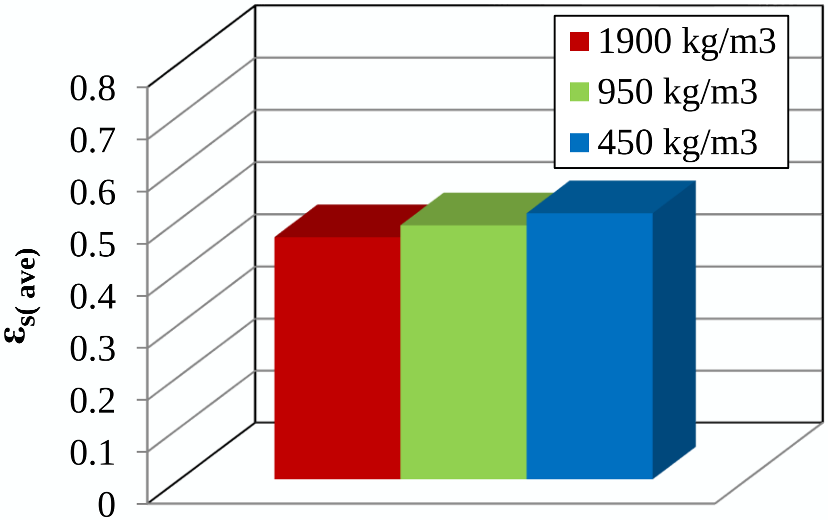
Higher drag force → Reduced wall friction



Smaller F_c/F_d causes less wall normal force from the solids



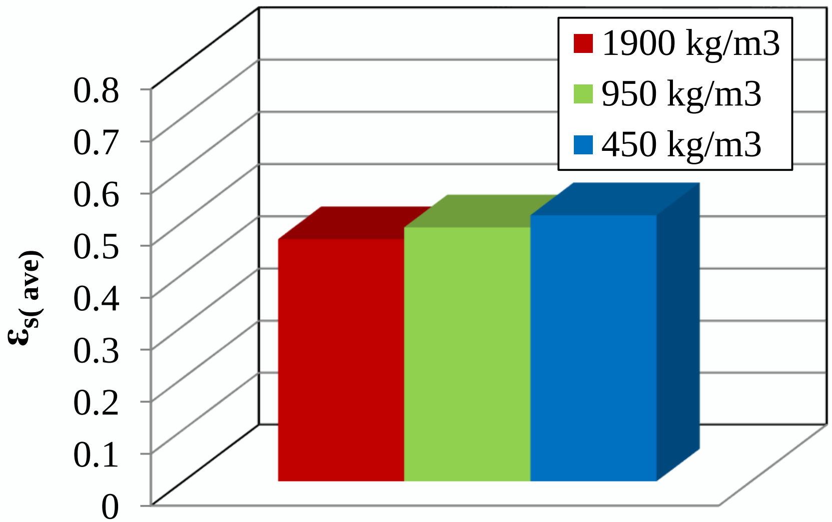
Solids volume fraction



Dense bed regime over a wide range of material density

Higher centrifugal force from rotation → Solids bed becomes more compact

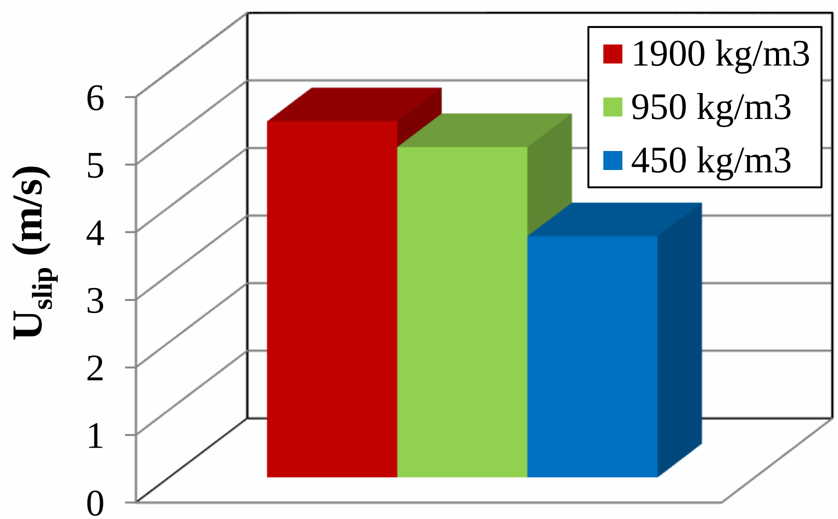
Slip velocity



Dense bed regime over a wide range of material density

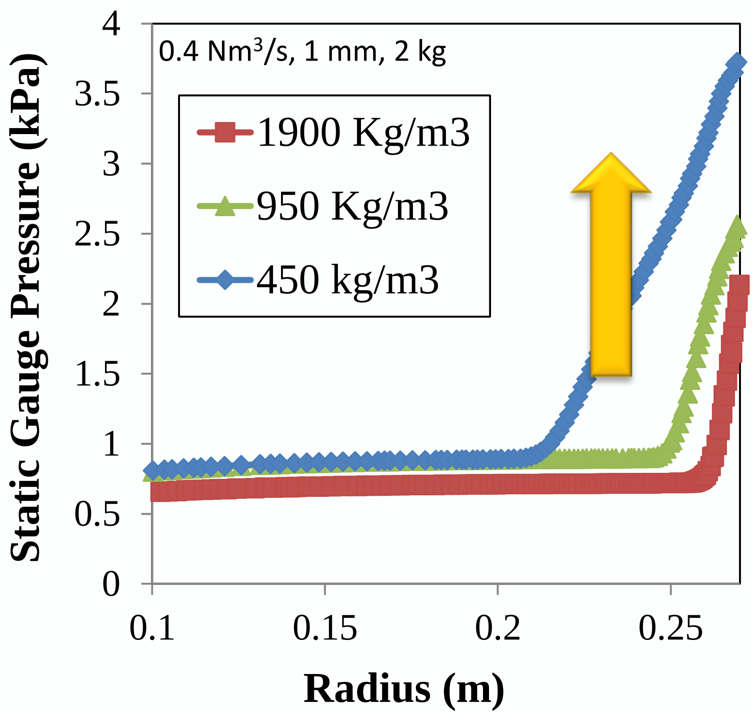
Higher centrifugal force from rotation → Solids bed becomes more compact

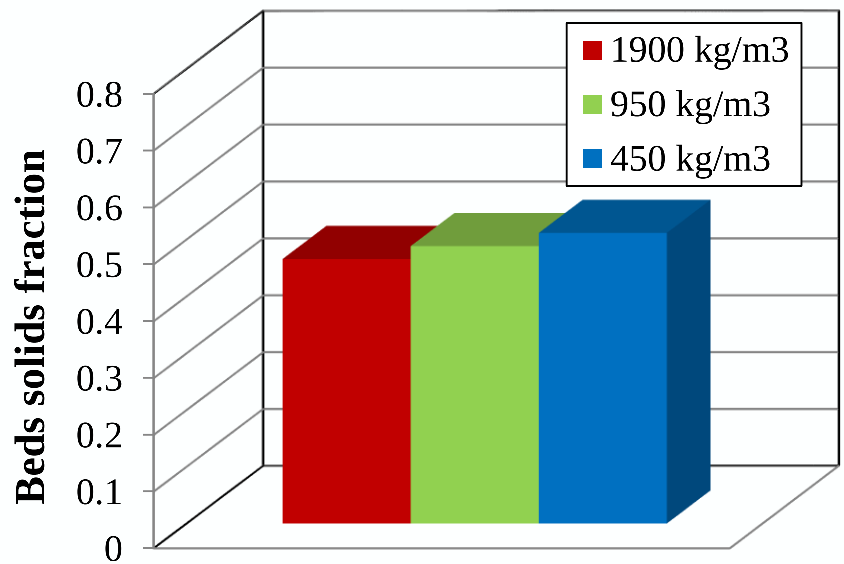
Increased solids velocity → Decreases relative velocity between phases



Same order of magnitude of slip velocities observed

Summary





- Pressure drop over the solids bed increases with decreasing solids density
- Decreasing density of material leads to increase in both drag force and centrifugal force over the bed at the given flow rate
- Dense bed is obtained without particle entrainment for different density materials for a given flow rate

Outline

- Introduction
- Numerical methodology
- **Results and discussion**
  - *Effect of gas flow rate*
  - *Effect of particle density*
  - *Effect of particle diameter*
- Conclusions

Gas flow rate: 0.4 Nm^3/s
Material: HDPE (950 kg/m^3)
Bed mass: 2 kg

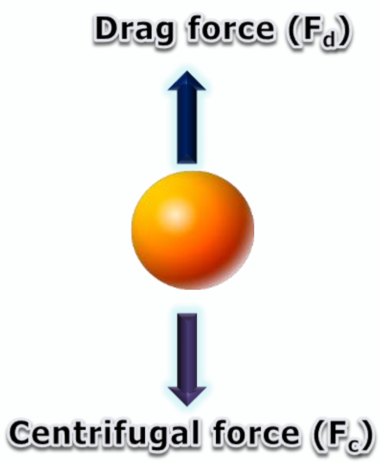
Particle diameter:

1 mm
0.5 mm

Key flow features investigated:

- Bed pressure drop
- Fluidization regime
- Bed solids volume fraction
- Slip velocities between phases

Effect on drag force



Drag force $\propto$ Total cross section of solids

$$\text{Total cross section available in solids } (A_T) = \left(\frac{A_P}{V_P}\right) \times V_T$$

Where, $\left(\frac{A_P}{V_P}\right)$ – specific cross sectional area

V_T - total volume of solids in the system

$$V_P = \frac{\pi d_p{}^3}{6}$$

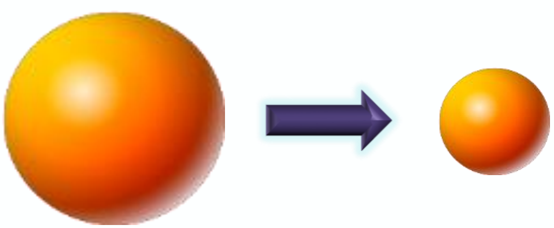
$$A_P = \pi d_p{}^2$$

Now, particle density and mass in each system constant,

$$(V_T) = \text{constant}$$

However, since particle density decreases and mass of solids is kept constant,

$$\left(\frac{A_P}{V_P}\right) \uparrow \qquad A_T \uparrow$$



$$\left(\frac{A_P}{V_P}\right) < \left(\frac{A_P}{V_P}\right)$$

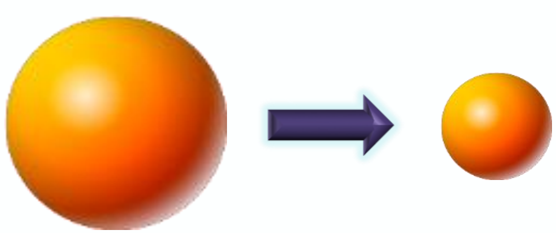
Drag force on bed increases due to higher solids cross sectional area

GSVR pressure profile

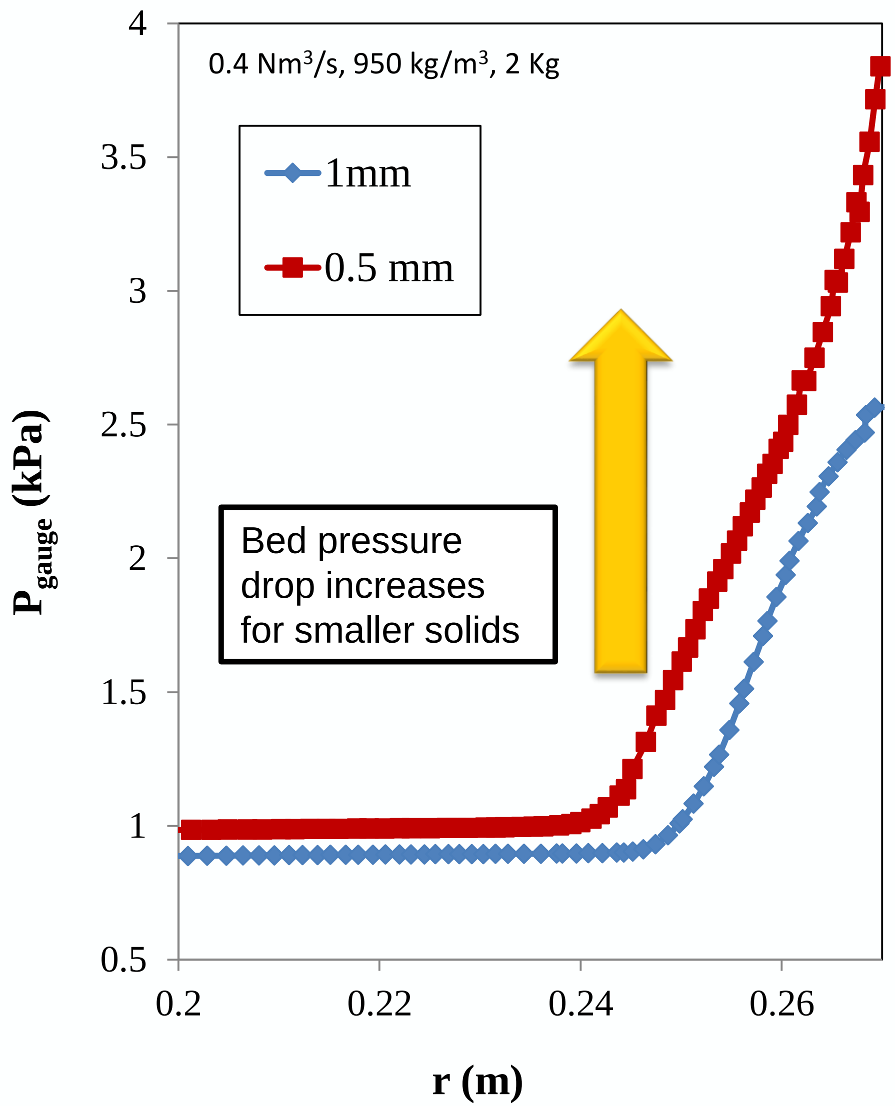
Higher drag force → Higher bed pressure drop

$$V_P = \frac{\pi d_p^{\ 3}}{6}$$

$$A_P = \pi d_p^{\ 2}$$



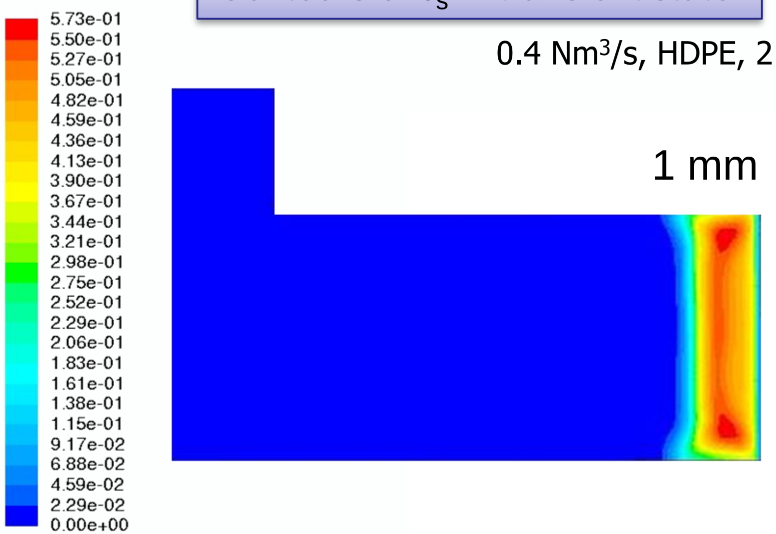
$$\left(\frac{A_P}{V_P}\right) < \left(\frac{A_P}{V_P}\right)$$



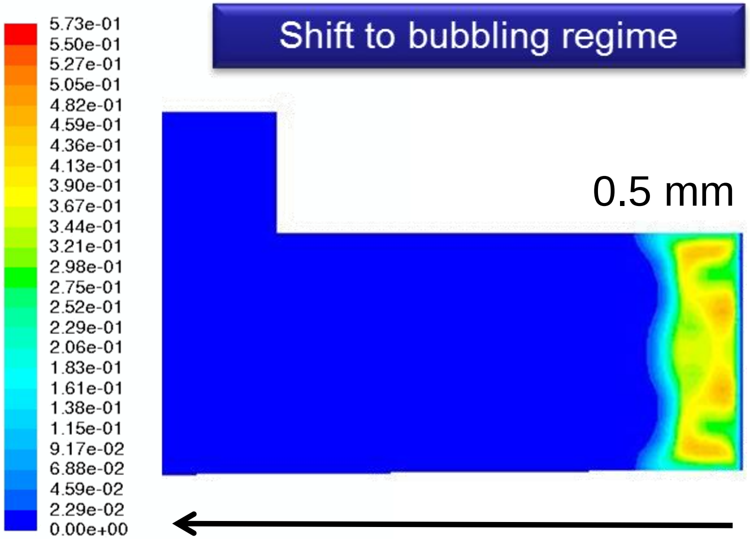
Fluidization regime

Contours of ε_s in transient state

0.4 Nm³/s, HDPE, 2 Kg

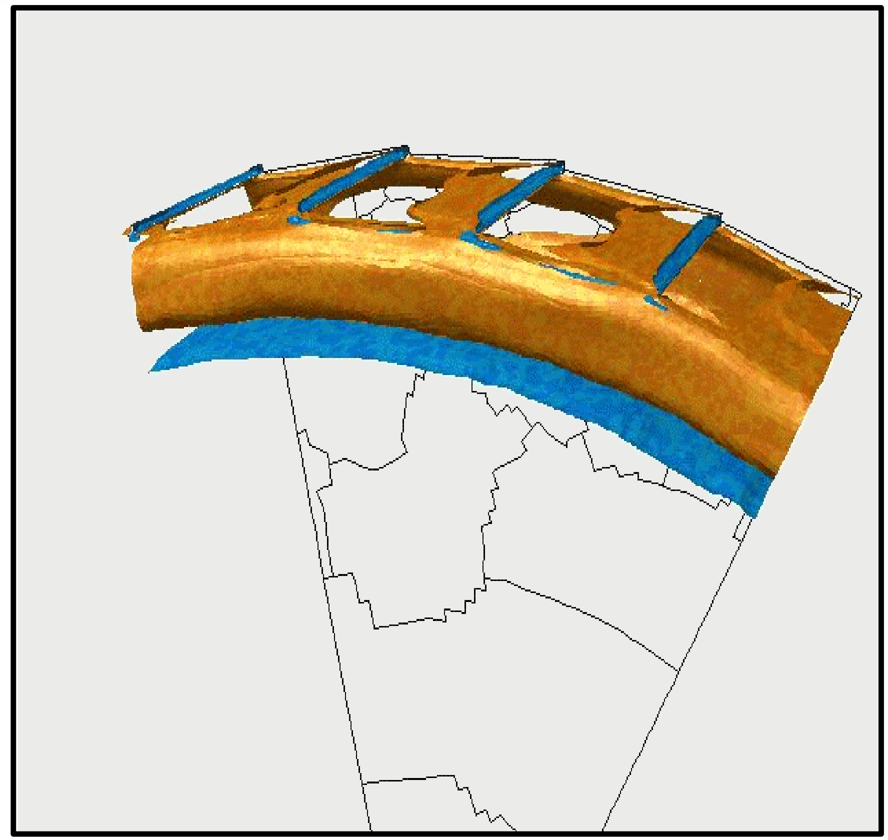


Shift to bubbling regime



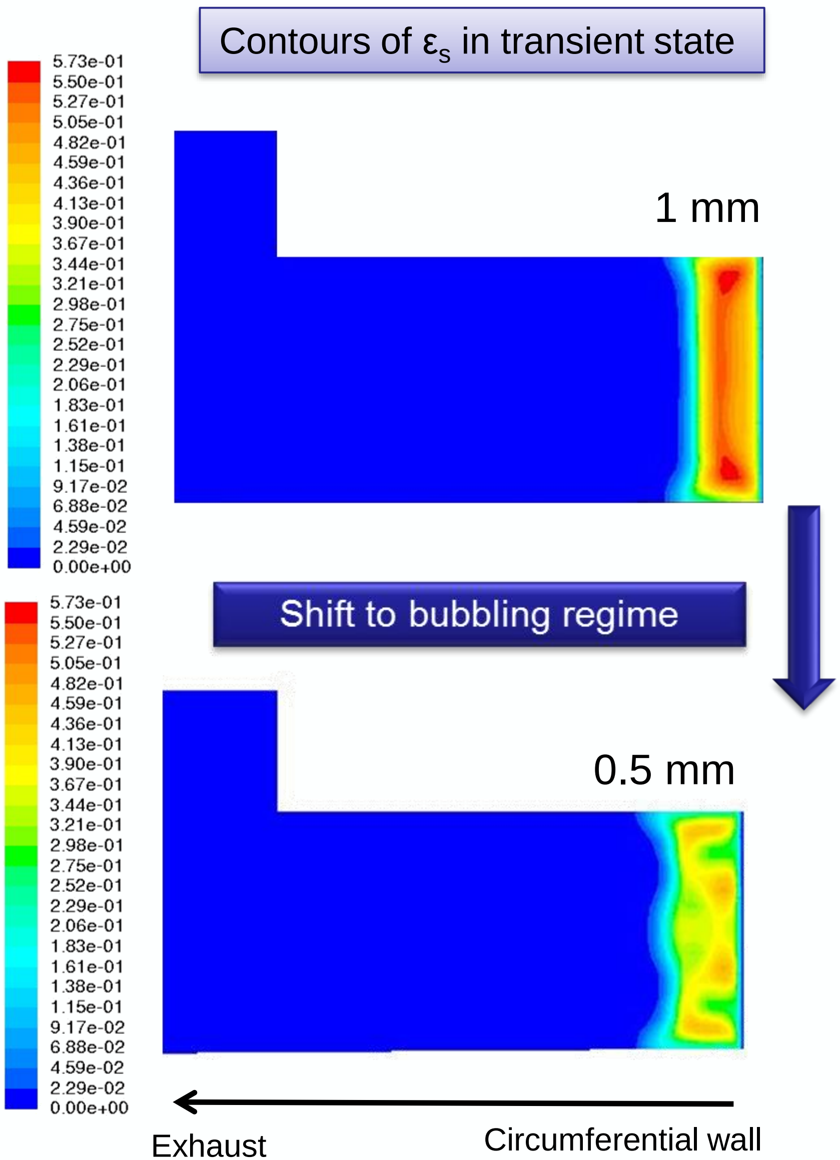
Exhaust ← Circumferential wall

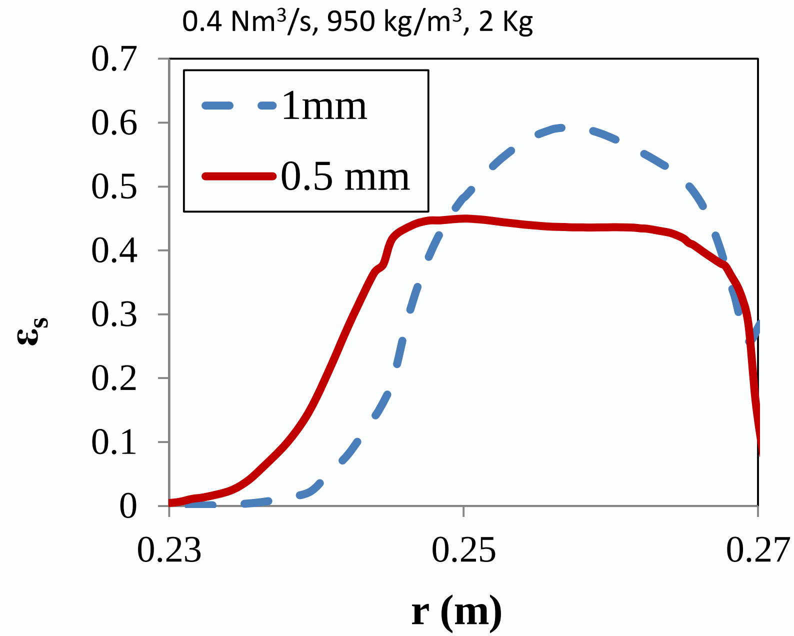
0.4 Nm³/s, HDPE, 0.5 mm, 2 Kg



Iso-surface of solids fraction: 0.4 (yellow) and 0.1 (blue) in the GSVR

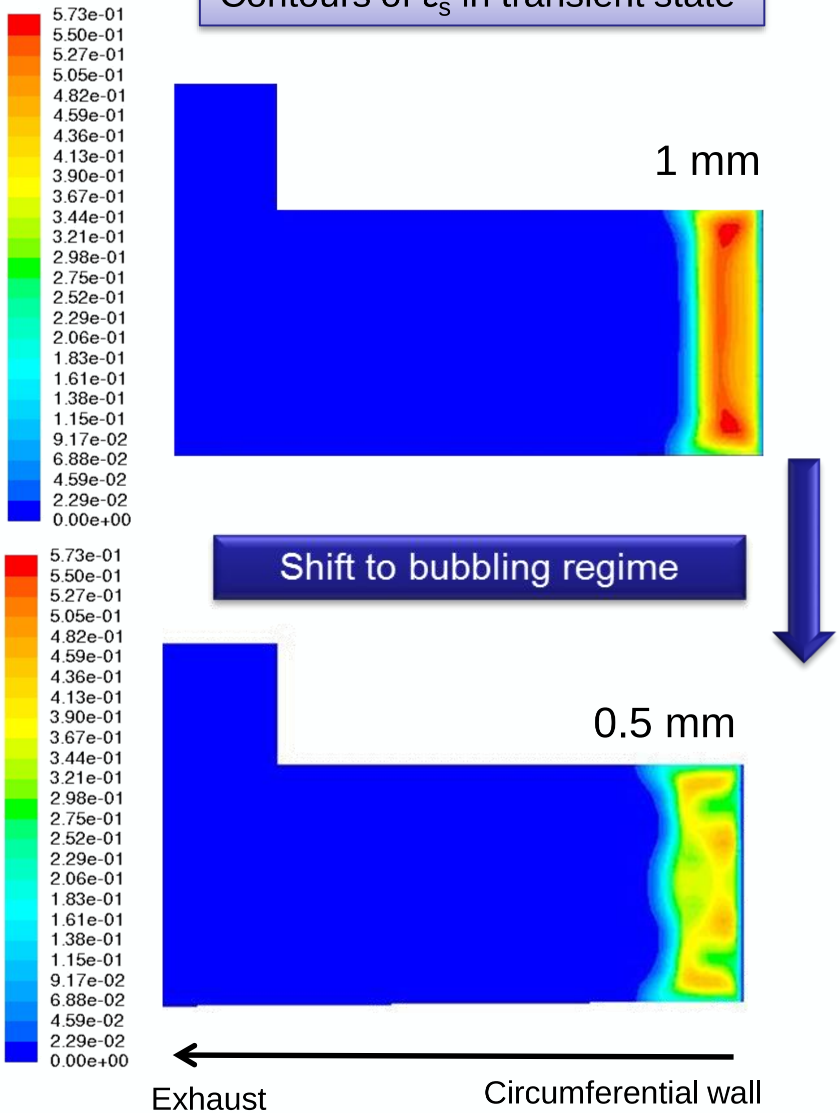
Solids volume fraction

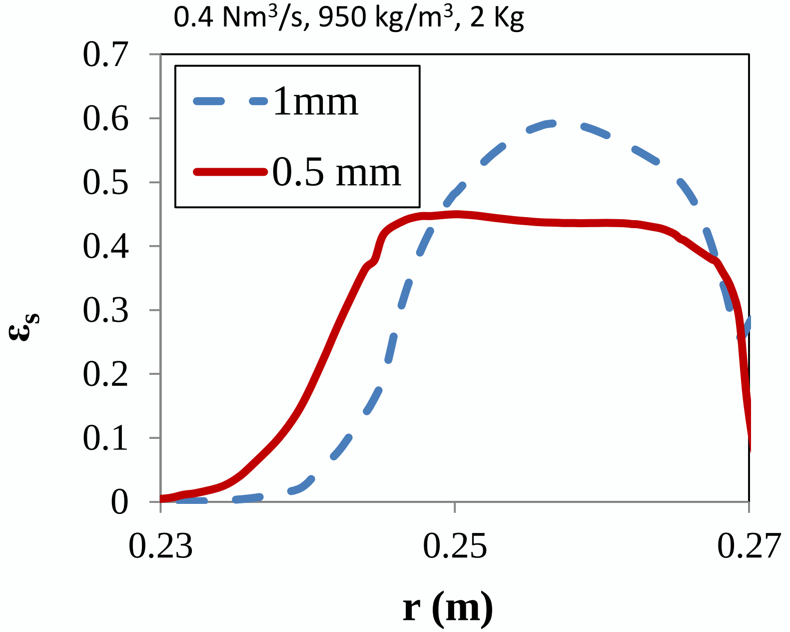


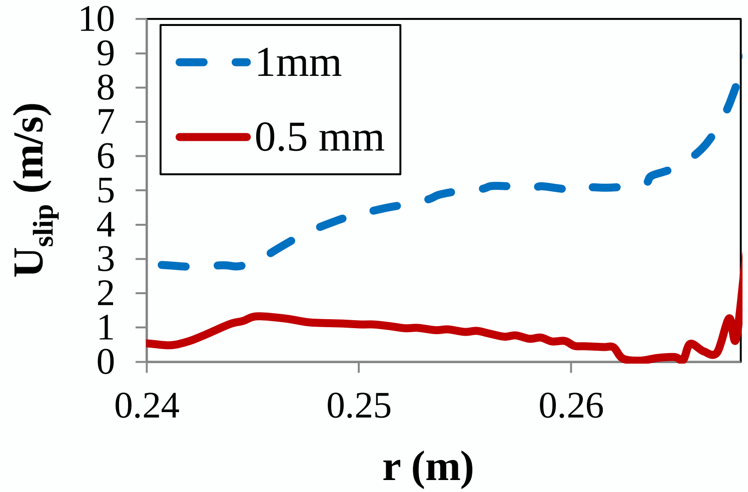


Solids volume fraction

Contours of ε_s in transient state



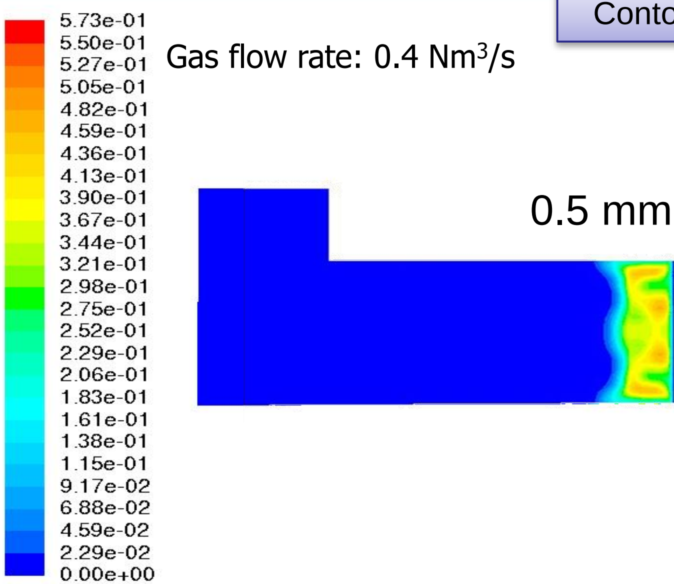


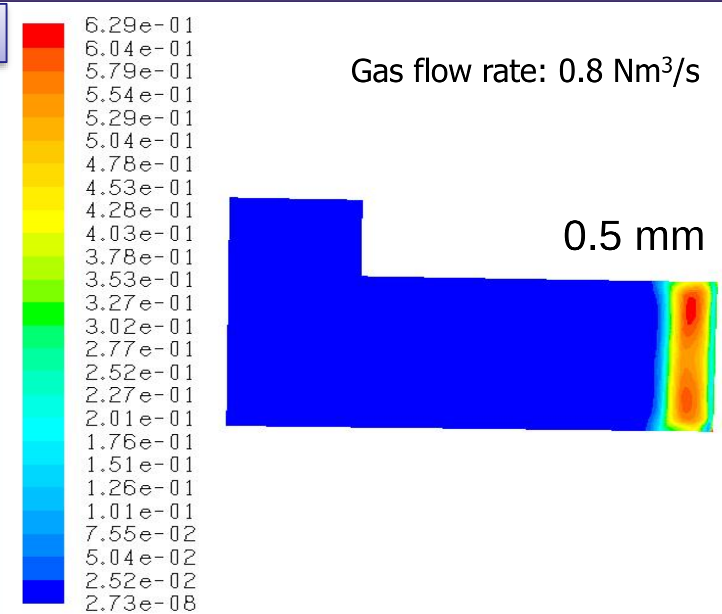


Slip velocity significantly falls due to bubbling

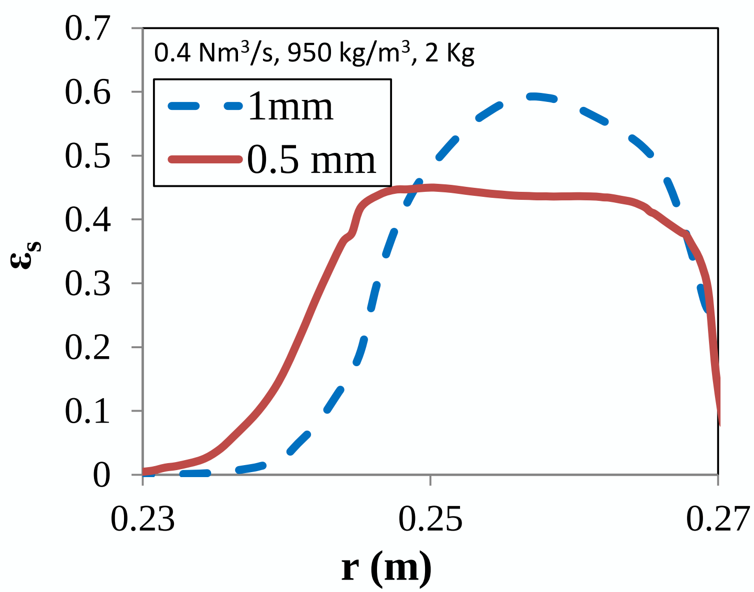
Effect of gas flow rate

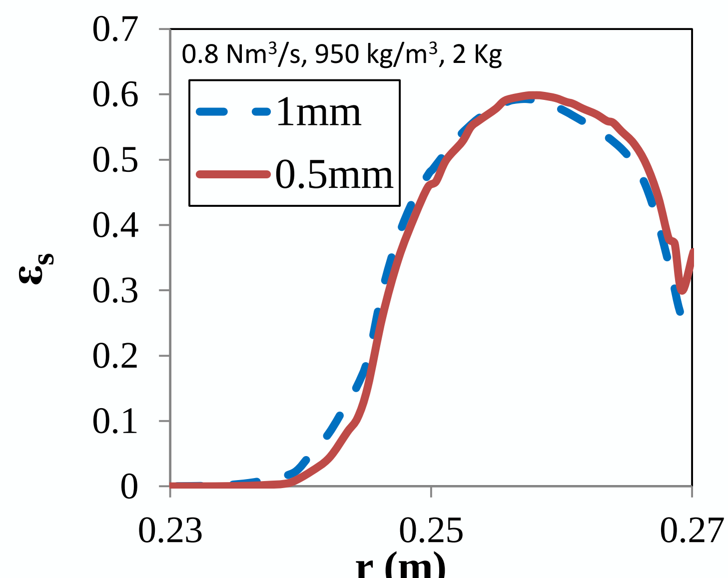
Contours of ε_s in transient state





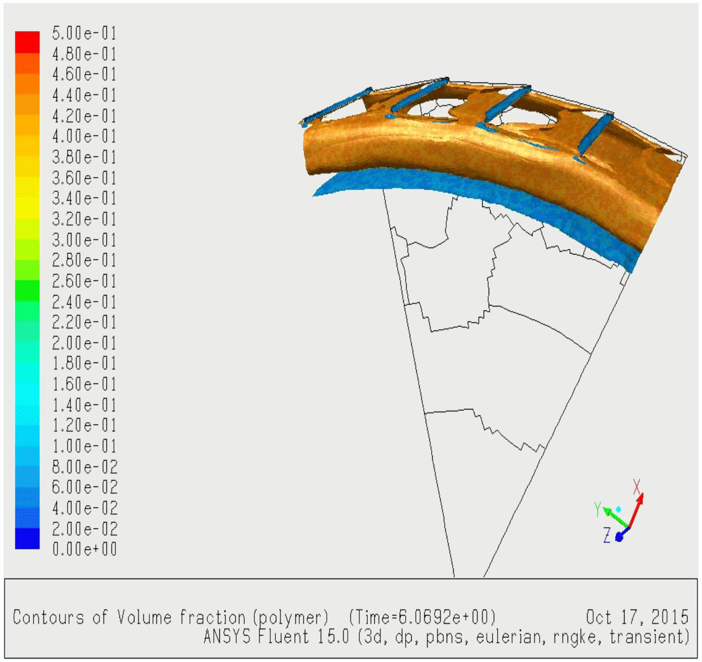
Bubbling diminishes





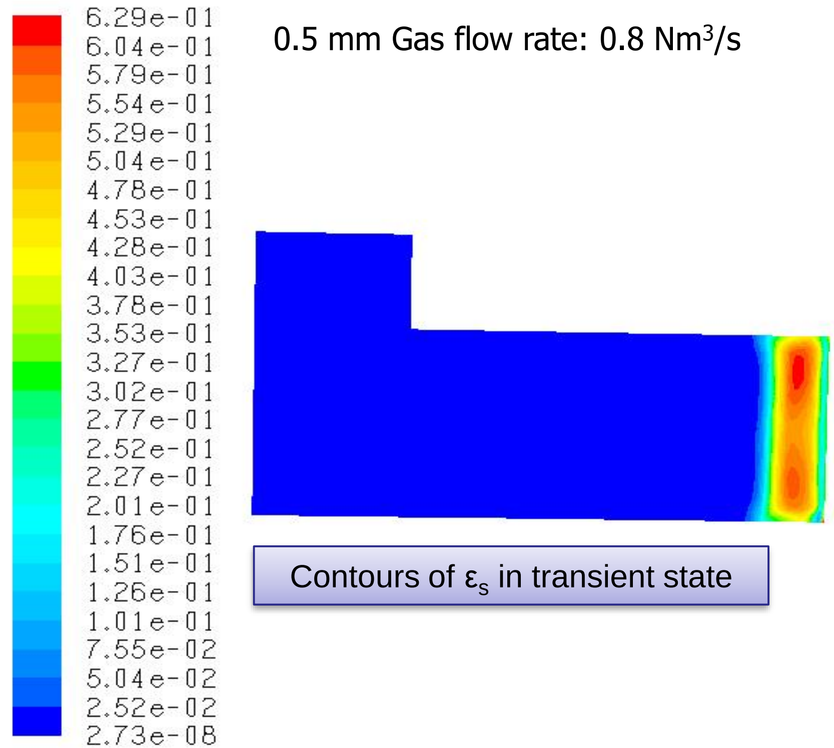
Summary

0.5 mm Gas flow rate: 0.4 Nm^3/s



Iso-surfaces of solids fraction: 0.4 and 0.1 in the GSVR

0.5 mm Gas flow rate: 0.8 Nm^3/s



Contours of ε_s in transient state

- Decreasing particle diameter increases pressure drop over the solids bed
- Fluidization regime changes from uniform dense to bubbling flow regime
- Increasing gas flow rate diminishes bubble formation in bed

Outline

- Introduction
- Numerical methodology
- Results and discussion
  - *Effect of gas flow rate*
  - *Effect of particle density*
  - *Effect of particle diameter*
- Conclusions

Conclusions

- The GSVR achieves high gas-particle slip velocities without particle entrainment at high gas flow rates
- The solids bed formed is comparatively dense and uniform over the wide range of gas flow rates and particle density studied
- Bubbling bed behavior may develop in the GSVR depending on the gas throughput and particle diameter
- Increasing gas flow rates in bubbling regime in GSVR does not entrain particles as opposed to the conventional fluidized beds; rather diminishes bubbling making the bed more uniform

Acknowledgement

Thank you for your attention!

The research leading to these results has received funding from:

- the **European Research Council** FP7/2007-2013/ ERC grant agreement n° 290793
- VSC (Flemish Supercomputer Center), funded by Ghent University, the Hercules Foundation and the Flemish Government – department EWI

List of Symbols

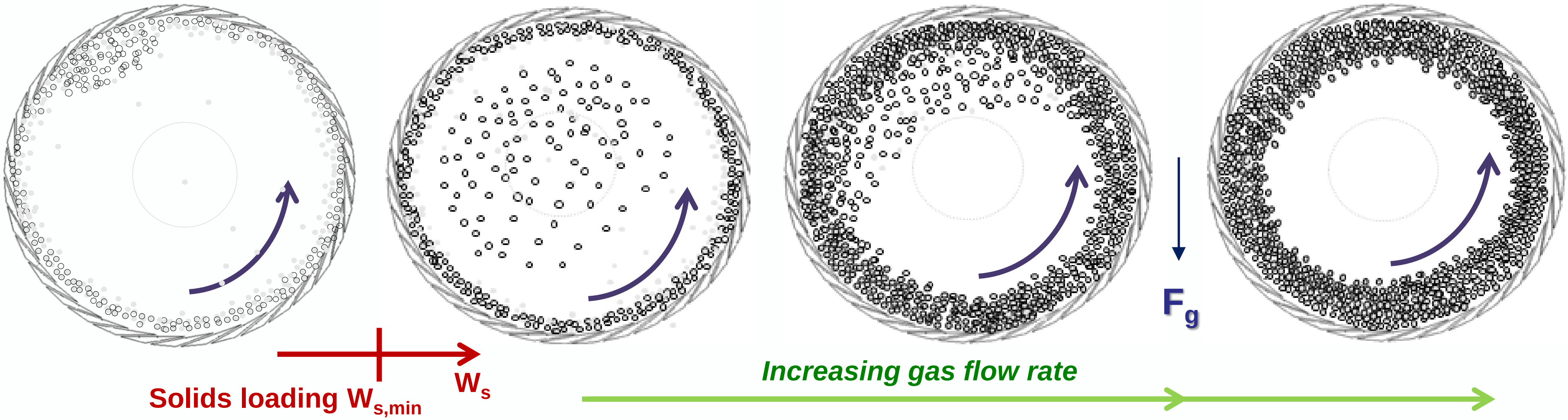
D_R: reactor diameter [m]
D_E: exhaust diameter [m]
L_R: length of GSVR [m]
I_O: slot thickness [m]
α: slot angle
HDPE: High-Density Poly-ethylene
G_M: gas flow rate [Nm^3/s]
r: radial coordinate [m]
P_{gauge}: static gauge pressure [kPa]
ΔP_{bed}: bed pressure drop [kPa]
ε_s: local solids volume fraction
$\varepsilon_{s\,(ave)}$: spatially-averaged solids volume fraction
$U_{\theta(s)}$: azimuthal solids velocity [m/s]
$U_{\theta(g)}$: azimuthal gas velocity [m/s]
U_{slip}: slip velocity [m/s]
Nu: Nusselt number
Re: Reynolds number
F_C: centrifugal force [N/m^3]
F_D: drag force [N/m^3]
A_P: cross sectional area of single particle [m^2]
V_P: volume of single particle [m^3]
V_T: total cross sectional area [m^2]

Mail me at: Geraldine.Heynderickx@Ugent.be

Thank you for your attention!

Image courtesy: www.Dilbert.com

Bed stability



unstable bed		semi-stable bed	stable bed
below $W_{s,min}$ ➢ slugging ➢ channeling	**above** $W_{s,min}$ ➢ non uniformity	➢ "fall-out" at the top ➢ $W_{s,max}$ increases at higher gas flow rate	➢ uniformly rotating ➢ $W_{s,max}$ increases at higher gas flow rate
	Particles all over the front plate	***Limited number of particles in the freeboard***	***No "fall-out"***

Bed stability depends on gas flow rate, particle diameter, density and loading

Glossary

Freeboard – volume of the chamber between the central outlet and the edge of the bed, where solids fraction is significantly reduced

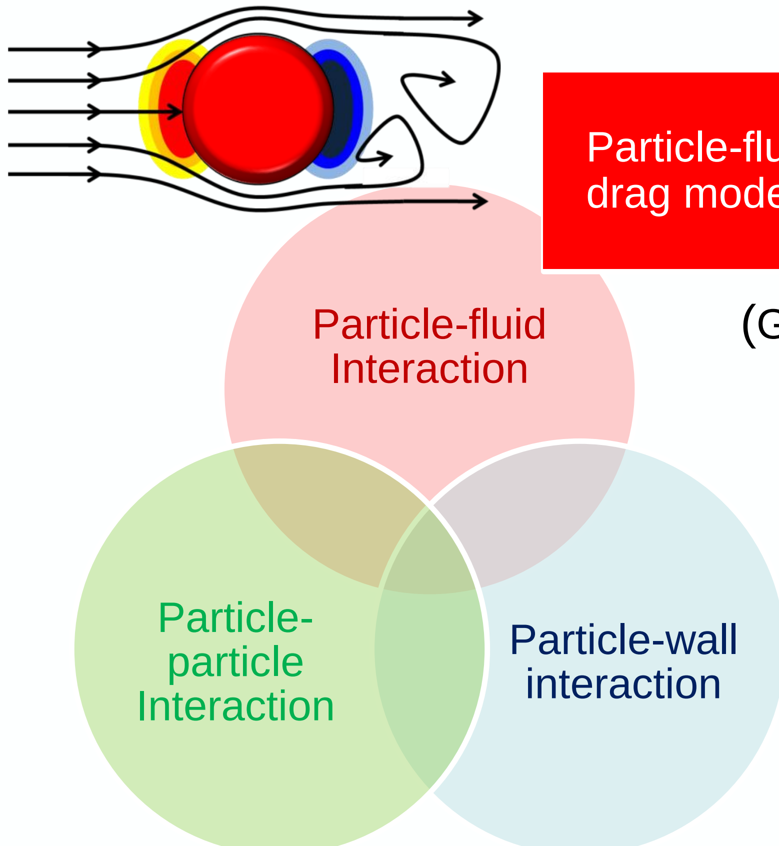
Slip velocity – Relative velocity of gas phase with respect to solids phase

Bed pressure drop – Difference of static gauge pressure before and after the solids bed

Bed density – Characterized by the volumetric average solids fraction inside the bed

Uniform bed – Bed with no spatial variation of solids volume fraction in azimuthal, axial and radial directions

Tuning of parameters

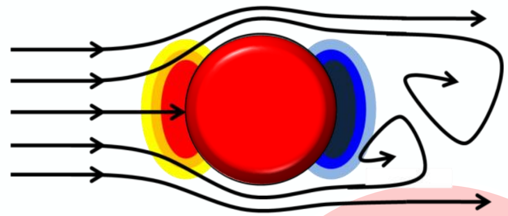


Particle-fluid drag models

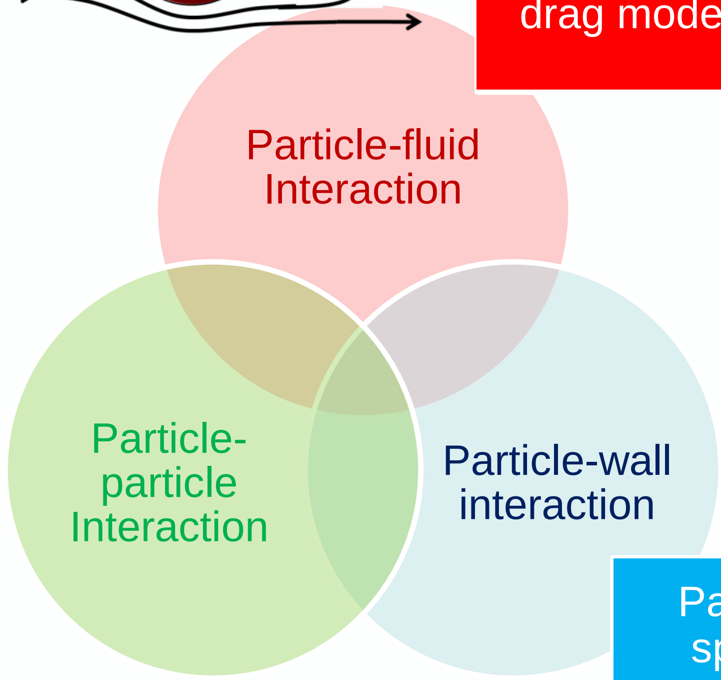
(Gidaspow[4], Syamlal O'Brien[5])

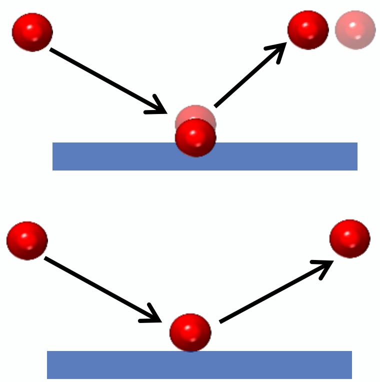
Effect of drag models on GSVU flow was found to be minimal; Gidaspow drag model was chosen to be used further

Tuning of parameters



Particle-fluid drag models



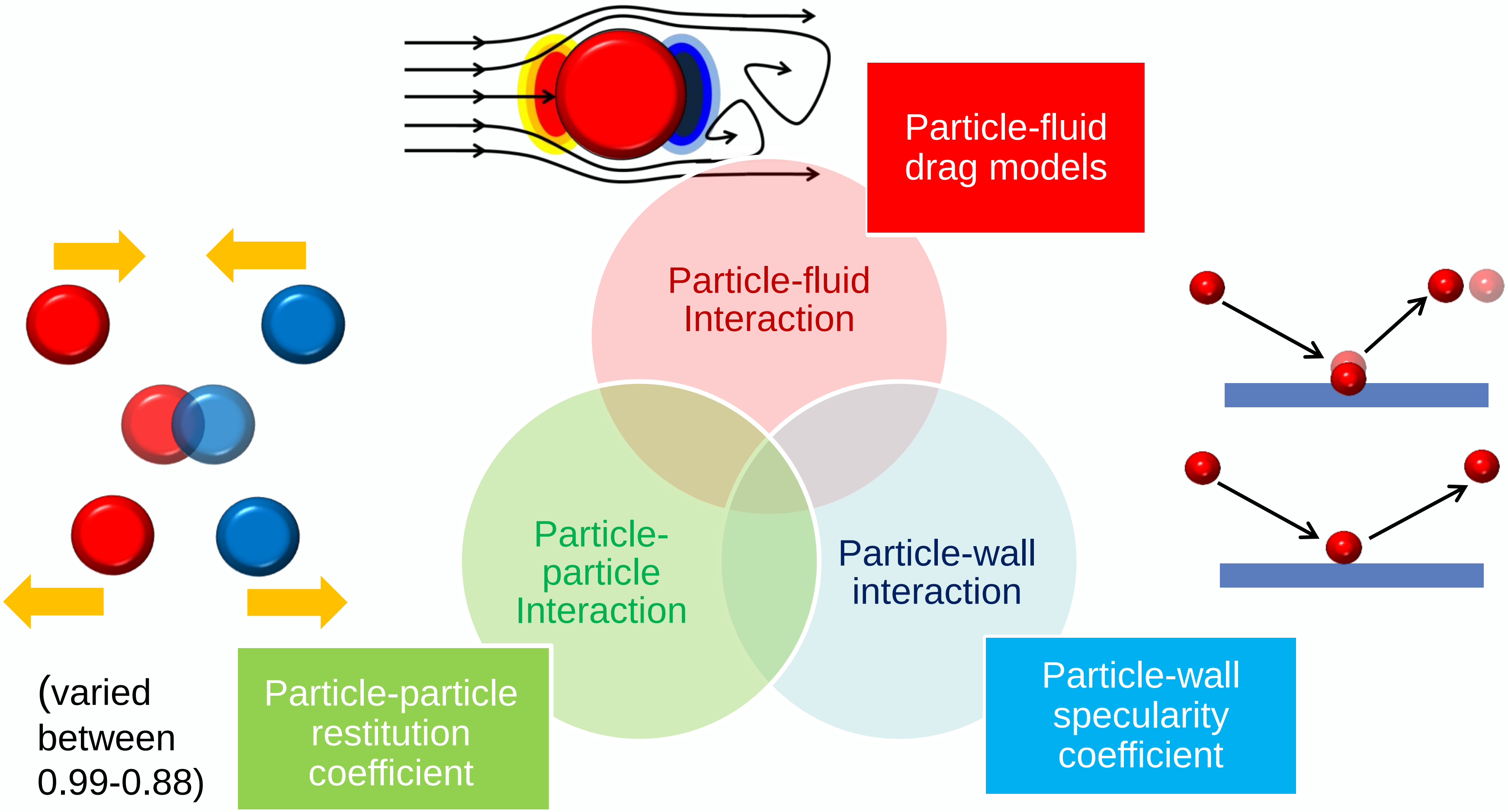


Particle-wall specularity coefficient

(varied between 0.1-0.001)

- Increasing solid-wall specularity coefficient increases particle-wall friction
- The circumferential wall has more frictional effect than the end walls
- Best results are obtained at: particle end-wall coefficient – 0.004
  particle circumferential-wall coefficient – 0.02

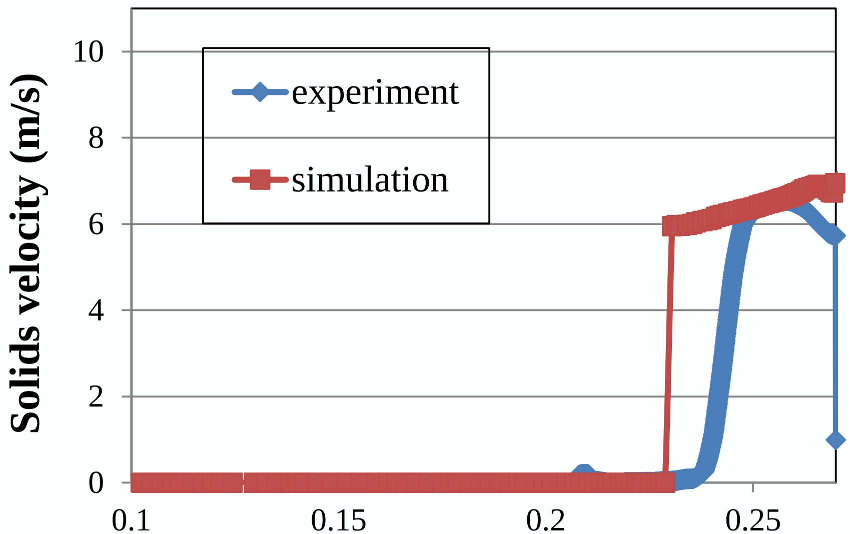
Tuning of parameters



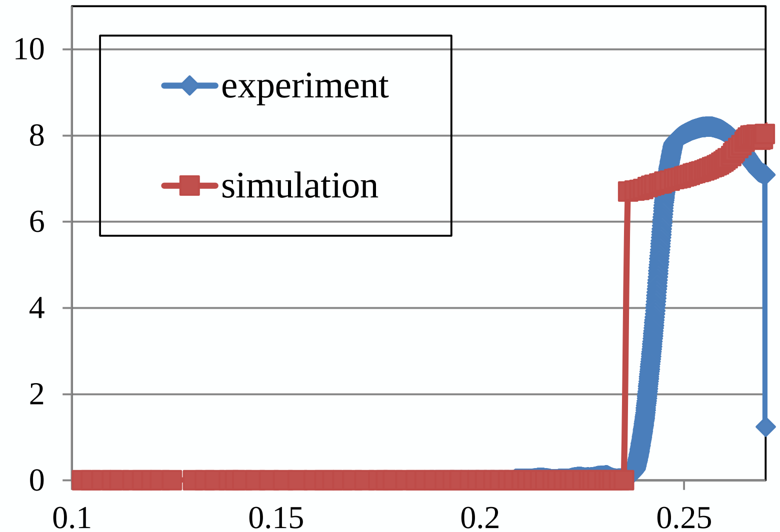
- Simulation data was found to be highly sensitive to restitution coefficient
- Best results are obtained at: particle-particle coefficient – 0.9 (mostly elastic collisions)

Validation with Experimental data

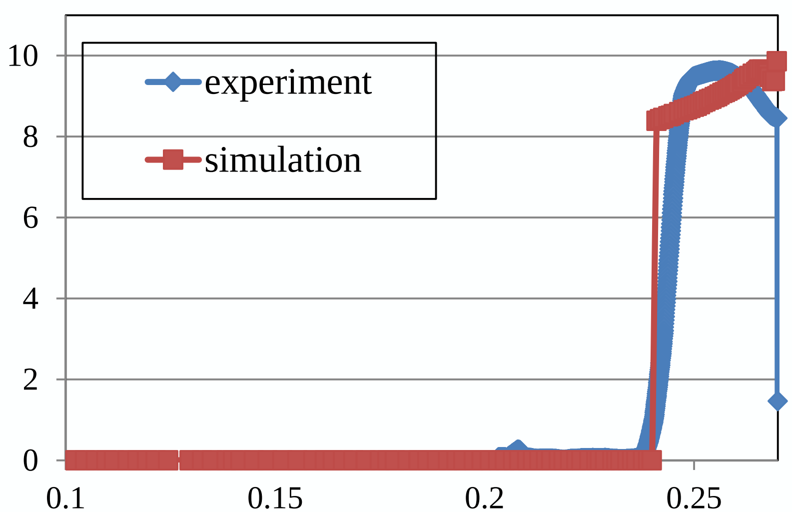
(High Density Polyethylene(HDPE), 1 mm, 2 Kg)



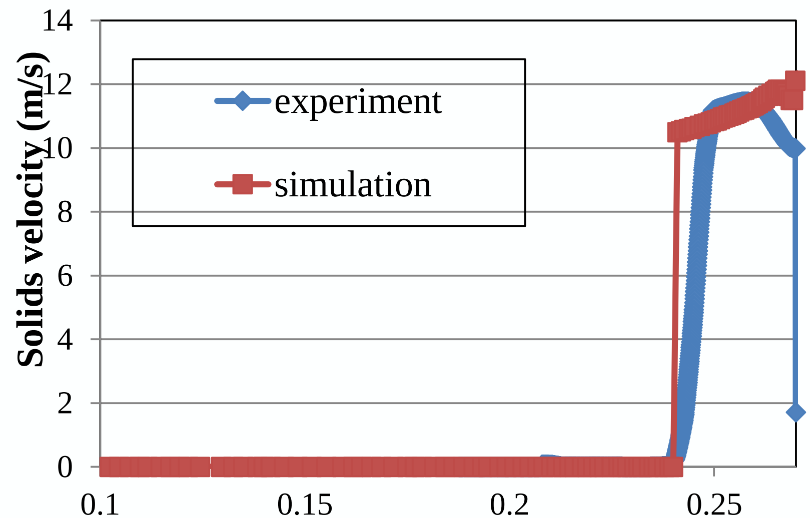
Gas mass flow rate: 0.484 Nm^3/s



Gas mass flow rate: 0.617 Nm^3/s



Gas mass flow rate: 0.749 Nm^3/s



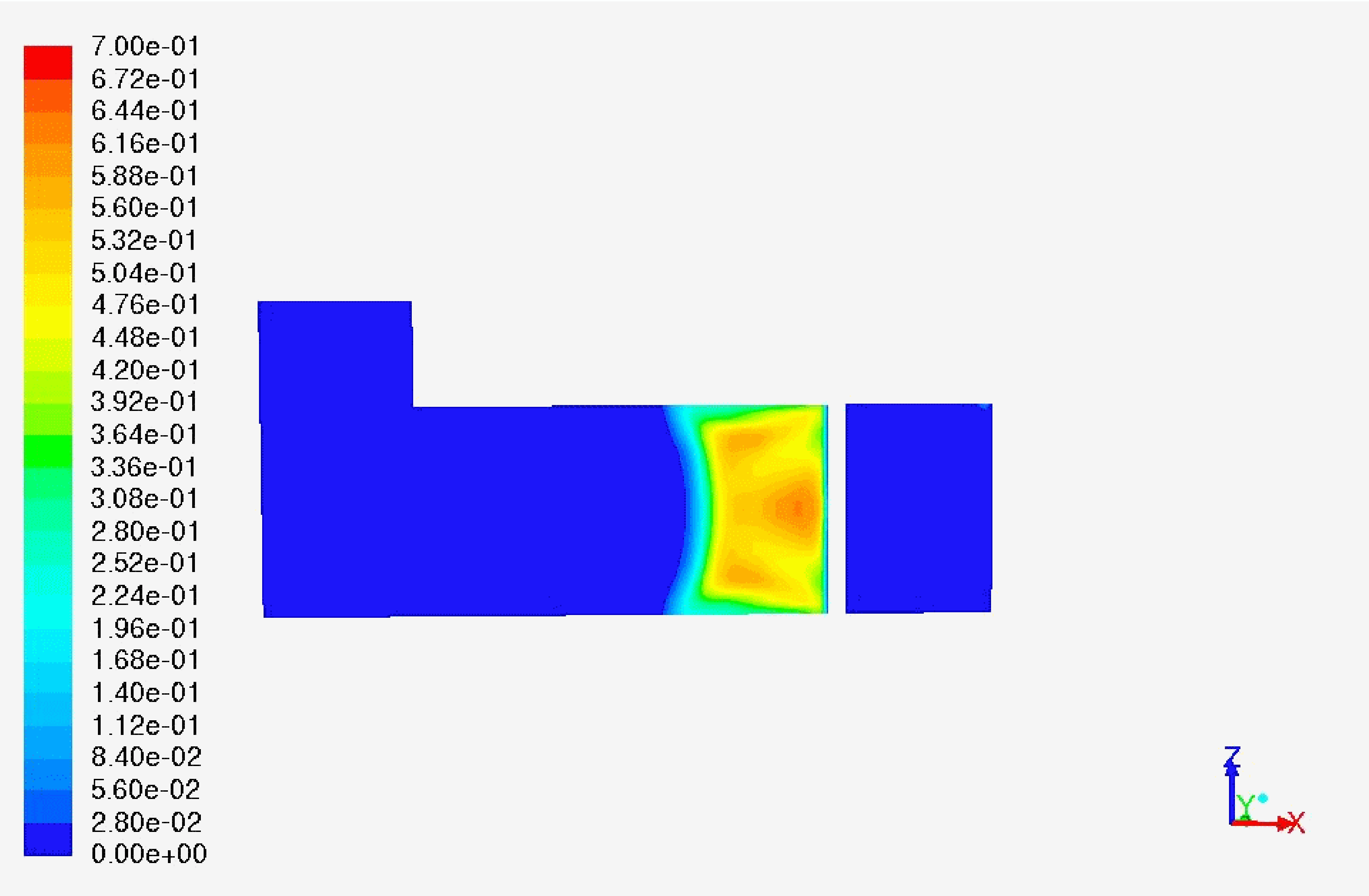
Gas mass flow rate: 0.881 Nm^3/s

Validation with Experimental data

	GSVR[1]	Static FB [2]
Volume (m^3)	0.023	0.00039
Gas-to-biomass ratio (kg_{gas} /$kg_{biomass}$)	**6.4**	**6.4**
Sand mass in reactor/volume (kg/m^3)	217	322
Supplementary heating	no	yes
Outlet Temperature (K)	772	790
Gas-phase residence time (s)	~0.05	~0.75
Product Yields (wt% of fed biomass):		
Tar	82.1	63.4
Pyrolysis gas	9.8	21.5
Char	7.7	14.4
Biomass (unconverted)	0.0	0.6
Biomass conversion rate/volume ($kg/m^3{\cdot}s$)	1.5	0.07

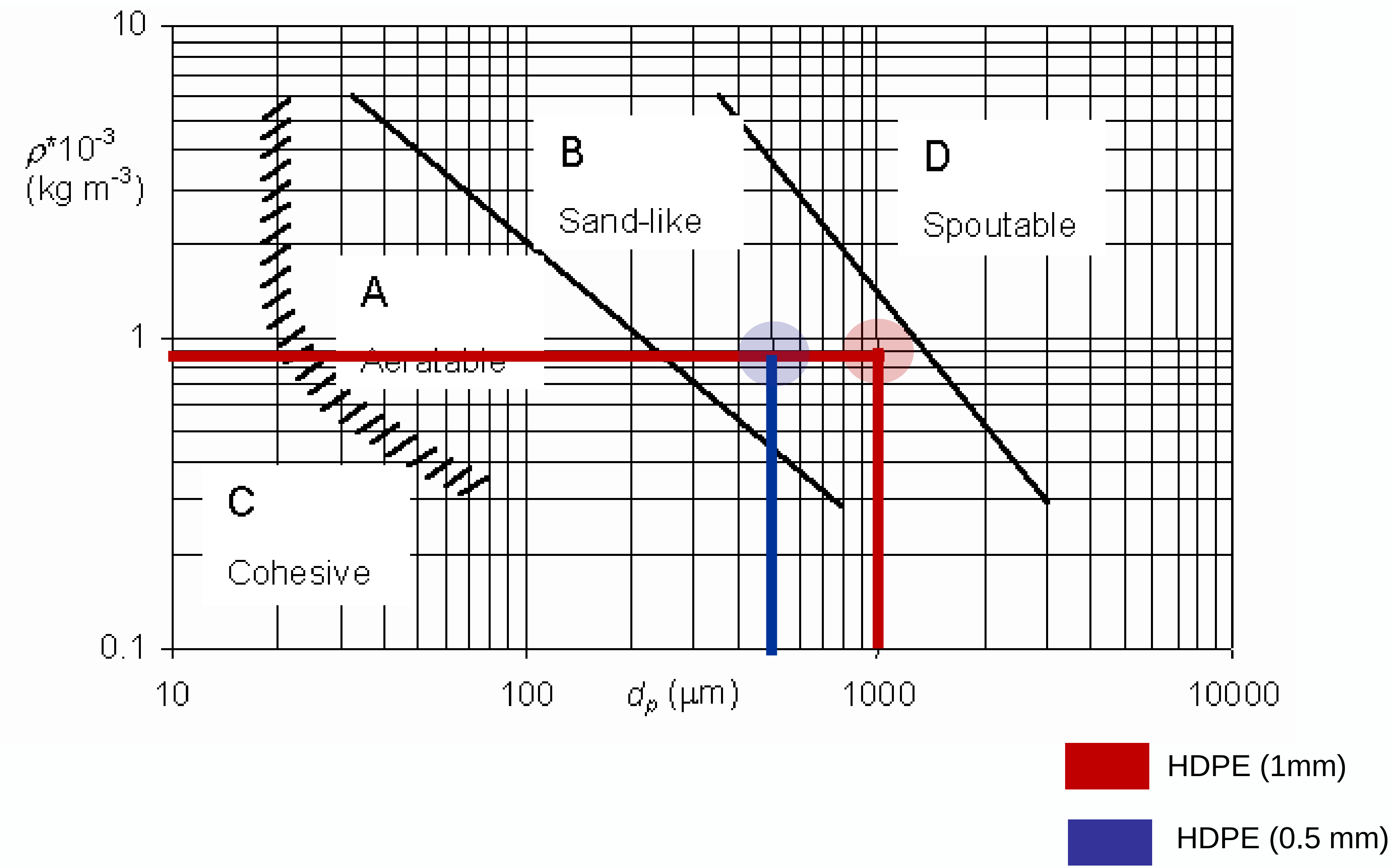
1:Ashcraft, Heynderickx and Marin, Chem. Eng. J. 207 (2012) 195
2. Xue, Heindel, and Fox, Chem. Eng. Sci. 66 (2011) 2440

450 kg/m³, 0.5 mm



Contours of Volume fraction (polymer) (Time=6.1440e+00) Nov 05, 2015
ANSYS Fluent 15.0 (3d, dp, pbns, eulerian, rngke, transient)

Geldart chart- a comparison



1:Kunii, Levenspiel, Fluidization Engineering. Elsevier 2013